NASA Contractor Report

Preliminary System Requirements for Synthetic Vision

A. Both, J. Klein, S. Koczo, and T. Lamb

Final Report
Contract NCA1-125, Task 11.10.4
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Rockwell Collins
Advanced Technology Center
Cedar Rapids, IA

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Preliminary System Requirements for Synthetic Vision

Revision history:

June 17, 1999	The “AGATE RESTRICTED INFORMATION” notice that was erroneously included on the title page of the first printing of this document was removed. The restriction notice should not have been included on this document

Preliminary System Requirements for Synthetic Vision

Abstract

Rockwell Collins, Inc. and subcontractors Jeppesen and Embry Riddle Aeronautical University conducted a study of preliminary system requirements for Synthetic Vision under NASA Contract NCA1-125, Task 11.10.4.

The primary focus of this study was to address how Synthetic Vision can be used to enhance the safety of flying. The approach taken in this study was to use the available public research data to determine the causal factors of controlled flight into terrain (CFIT) and loss of control (LOC) accidents. A determination was then made to identify corrective actions that would prevent these types of accidents. Based on these corrective actions, candidate synthetic vision applications were postulated that provide the needed capability to the flight crew to eliminate the factors that contribute to CFIT and LOC accidents. Based on these candidate synthetic vision system applications, requirements and key issues were identified, along with potential solutions. In addition to safety, this study also addressed potential uses of Synthetic Vision that may provide operational benefits and efficiencies. This study sought operational scenarios that could benefit from Synthetic Vision and then developed system requirements and issues associated with synthetic vision technology. The study identified numerous issues concerning synthetic vision applications, databases, retrofit, certification, and liability.

Preliminary System Requirements for Synthetic Vision

Acknowledgments

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Preliminary System Requirements for Synthetic Vision

Executive Summary

This report documents the findings of a study into Synthetic Vision Systems (SVS). The purpose of this study is to examine top-level SVS applications that may provide safety and operational benefits, and to identify requirements, issues and potential solutions concerning future implementation of these SVS applications in new and retrofit aircraft. The results of this study provide the foundation for future research into the development of Synthetic Vision Systems.

Scope

In June 1998, Rockwell Collins, Inc. was contracted to identify potential applications for Synthetic Vision Systems (SVS) and define preliminary system requirements. More importantly, Rockwell Collins, Inc. was tasked to study potential issues related to SVS implementation specifically in the areas of Databases, Aircraft Display Retrofit, Certification and Liability. Due to the expansive nature and complexities of the problem, Rockwell Collins, Inc. and NASA decided to include the expertise of Embry Riddle Aeronautical University and Jeppesen. This report represents the findings of this research team.

While the potential use for Synthetic Vision technology is wide and varied, this study was to specifically address how it could be used to enhance the safety of flying. The scope of the study specified that the following implementation categories be addressed:

- Warning systems
- Strategic systems
- Tactical systems

Where feasible, the research team has included references and findings relative to the wider market applications, such as improving aircraft / airline operational performance. Both the high-end market (business and regional aircraft up to air transport) and the low-end market (single and multi-engine general aviation) were addressed.

For the purpose of this study, a synthetic vision system is defined as a database derived system, which can aid the pilot's ability to visualize the aircraft situation relative to the environment outside the cockpit. This includes displaying warnings, alerts, advisories, and visualizations of terrain, obstacles, weather, other traffic, etc. In addition, use of database information may support strategic flight planning and tactical guidance applications that provide additional safety and operational benefits.

A synthetic vision system (SVS) relies on several databases to support the flight crew with information about the outside environment. Among these databases are:

- Geo-referenced databases
  - Terrain
  - Obstacles
  - Cultural features
  - Airport layout
- Weather databases
- Database information concerning traffic.

The focus of this study is on the geo-referenced databases and thus does not address the issues associated with weather and traffic. In addition, this study is primarily concerned with issues related to the use of synthetic vision databases. It does not address the use of enhanced vision sensors (EVS), which may also be used with SVS to provide the flight crew with additional situational awareness.

Approach to the Problem

As indicated, the primary focus of this study is to address how SVS can be used to enhance the safety of flying. Based on numerous studies, the accident categories of Controlled Flight Into Terrain (CFIT) and Loss of Control (LOC) have been identified as major contributors to aviation accidents and fatalities. This study uses these accident categories as a starting point in determining how SVS may help prevent these types of accidents in the future.

The approach taken in this study is to use the available public research data, such as Flight Safety Foundation reports, to determine the Causal Factors of CFIT and LOC accidents and to determine the Corrective Actions that would reduce / prevent these types of accidents from occurring in the future. Based on these Corrective Actions, Candidate SVS applications are postulated that provide the needed capability to the flight crew to eliminate the factors that contribute to CFIT and LOC accidents. Based on these Candidate SVS applications, SVS requirements and Key Issues are identified, along with potential solutions. Figure 1 summarizes the approach used to address SVS applications for safety. (Sections 2.3 and 2.4 of the report review CFIT and LOC accidents and their causal factors).

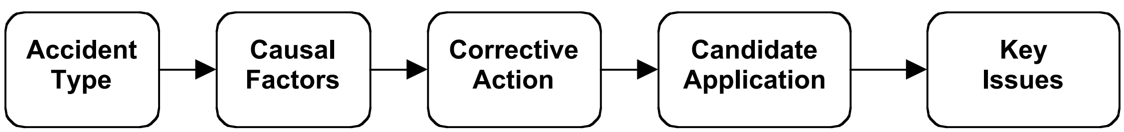

Figure 1 Systems Engineering Approach to Problem Solving

In addition to safety, this study also addressed potential uses of SVS that may provide operational benefits / efficiencies. Instead of addressing Causal Factors and Corrective Actions as for the safety study, the operational efficiency / benefits study attempted to identify operational scenarios that could benefit from SVS. Candidate SVS applications were identified and then examined against a generic SVS concept in order to derive system requirements and to identify key issues.

Generic Synthetic Vision System

Figure 2 provides a diagram of a generic synthetic vision system (SVS) that was used to assess top-level requirements and to identify key issues associated with the various SVS technologies / sub-systems. As indicated the synthetic vision system is a database derived system that relies on the geo-referenced databases of terrain, obstacles, etc., weather, and traffic databases. These databases, along with aircraft position and state information are integrated by the SVS applications processing sub-system for subsequent display to the flight crew. As indicated by the non-shaded areas, the focus of this study is on the geo-referenced databases. Weather and traffic databases, and Vision Sensors technology are not addressed.

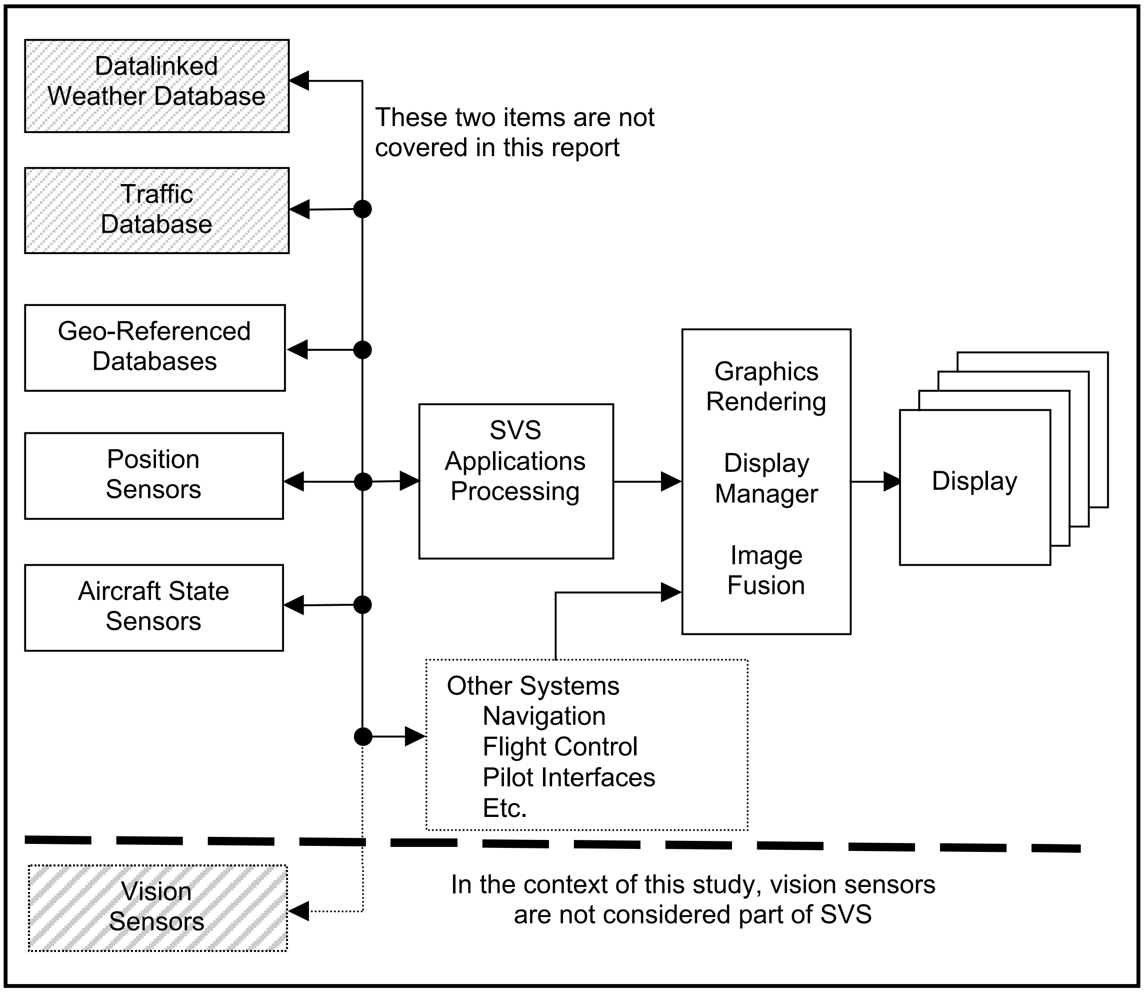

Figure 2 Generic Synthetic Vision System (SVS)

Candidate Applications

Table 1 summarizes the SVS applications that are identified in the study. The three categories of SVS applications are 1) Safety System applications, 2) Strategic applications, and 3) Tactical applications. The “Safety System” terminology was intentionally selected to differentiate warning / safety system from the strategic and tactical uses of SVS. Safety systems refers to the use of SVS as a “safety back-up system” to other systems. An example of a safety system is the Enhance Ground Proximity Warning System (EGPWS), also known more generically as Terrain Awareness Warning System (TAWS). Strategic and Tactical SVS systems are also capable of providing safety benefits, but these systems provide basic functionality associated with flying the aircraft, unlike the Safety System counterpart whose primary role is to provide hazard warnings / alerts.

SVS Application Category	Candidate SVS Applications	Potential Benefit
Safety System Applications (non-essential) (~10^{-5} integrity level)	Existing GPWS / EGPWS / TAWS / GCAS	Safety (terrain hazard alerting)
	TAWS Plus (next generation TAWS)	Safety (terrain hazard alerting)
	Take-off engine out procedure / situational awareness	Safety (terrain hazard alerting)
	Emergency landing in rough / smooth terrain	Safety (last resort guidance)
Strategic Applications (essential) (~10^{-7} integrity level)	Terrain strategic planning / replanning system	Safety and operational (flexible routes)
	Flight progress monitor	Safety and operational (flexible routes)
	Surface operations (situational awareness of airport layout / taxi routes)	Safety and operational (runway incursion protection, efficient taxiing)
Tactical Applications (critical) (~10^{-9} integrity level)	Vertical and spatial awareness during approach and landing (criticality / integrity dependent on whether application is used for safety / situational awareness or tactical guidance)	Safety (CFIT, loss-of-control prevention) or Safety (tactical guidance)
	Pathway-in-sky cues	Safety and operational (terrain safe routes, enhanced operations in terrain difficult areas in low-visibility conditions)
	Fly-the-image	Safety and operational (terrain safe routes, enhanced operations in terrain difficult areas in low-visibility conditions)
	Approach monitor (criticality / integrity in range of essential to critical, i.e., (~10^{-7} to 10^{-9} integrity)	Operational (lower landing minimums)
	Approach and landing aid, and Surface Operations (criticality / integrity in range of essential to critical, i.e., (~10^{-7} to 10^{-9} integrity)	Operational (reduced airport infrastructure)
	Navigation	No apparent advantage over conventional nav. guidance systems

Table 1 Summary of Potential SVS Applications and Anticipated Benefits

From Table 1 it is noted that Safety System SVS applications are relatively low integrity systems compared to Strategic and Tactical SVS applications. Strategic applications have moderate integrity requirements, while Tactical applications require the highest integrity due to their guidance role in flying the aircraft. It should be noted that the integrity categories specified in Table 1 are stated in general terms; actual integrity requirements must be developed on a case-by-case basis for each individual SVS application by the certification authorities.

As seen in Table 1, Safety System applications provide terrain hazard alerting and last resort guidance information. Strategic applications provide planning of terrain safe routes, monitor flight progress relative to terrain, and also provide support for airport surface operations. Tactical applications provide guidance to the flight crew throughout the various phases of flight.

Section 2 provides a discussion of a Generic Synthetic Vision System, and also develops Candidate SVS Applications. The applications in Section 2 address aircraft for the major and regional airlines, business, and general aviation users. Some of the applications are more applicable to one type of aircraft end user over another.

Terrain and Obstacle Database Requirements

Before discussing key issues identified in the study, it is beneficial to provide a brief summary of Terrain and Obstacle database requirements. These databases are the cornerstone of any successful implementations of SVS applications. Tables 2 and 3 summarize terrain and obstacle database requirements, respectively. Figure 3 provides an illustration of the operational areas associated with the flight phases used in the tables.

One of the key issues / enablers of SVS applications is the availability of terrain and obstacle data that meets the resolution and accuracy requirements as identified in Tables 2 and 3, while at the same time supporting the integrity (low-probability of undetected failures and errors) of the SVS applications themselves. The following paragraph briefly discusses the current roles of various US government agencies involved in providing terrain and obstacle databases. In the longer term, some of these agencies will need to coordinate an effort to provide more complete and higher integrity data to support the envisioned SVS applications.

Terrain Data	Airport	Takeoff / Landing	Departure / Approach	Enroute
Resolution	1 meter	6 arc-seconds	30 arc-seconds *	30 or 150 arc-seconds
Horizontal Accuracy	1 meter	30 meter	130 meter	130 or 1000 meter
Vertical Accuracy	1 meter	10 meter	30 meter	100 meter
Confidence	95%	90%	90%	90%

* could increase to 15 arc-second resolution for mountainous airports

Table 2 Terrain Database Requirements

Obstacle Data	Airport	Takeoff / Landing *	Departure / Approach *	Enroute **
Resolution	N/A	N/A	N/A	N/A
Horizontal Accuracy	1 meter	20 feet	50 feet	130 meters
Vertical Accuracy	1 meter	3 feet	20 feet	30 meters
Confidence	95%	90%	90%	90%

* Based on NGS, FAA 405 accuracy standards
** Based on NIMA DTED Level 1 accuracies

Table 3 Obstacle Database Requirements

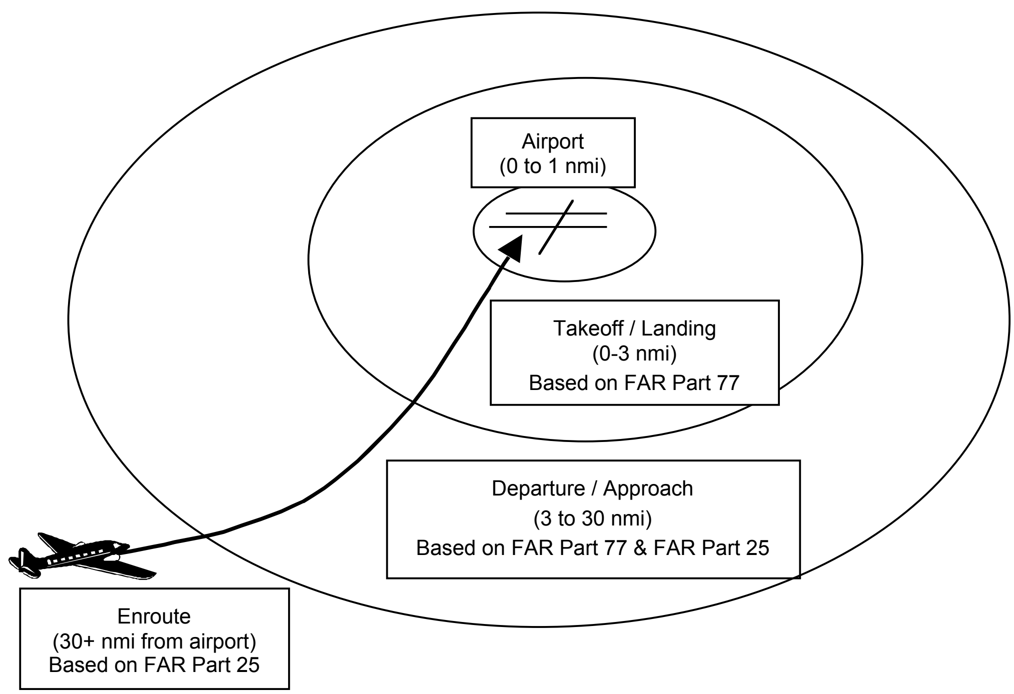

Figure 3 Flight Phase Operational Areas

US Government Agency Roles in Providing Source Terrain / Obstacle Data

The DOD has compiled a worldwide file of global terrain by combining, reducing and adjusting various surveyed databases with new and more accurate data. This data is compiled using the WGS-84 worldwide datum. As is noted in the study, a common, worldwide datum is required for consistent use of SVS databases in order to avoid offset errors in the location of terrain and obstacles. The DOD's cartography is handled under the National Imagery and Mapping Agency (NIMA), which provides timely, accurate imagery and geospatial information to support national security. The US Imagery and Geospatial Information System (USIGS) is an extensive group of organizations that interface with the DOD and include nonmilitary cartographic organizations. The US Department of Commerce has the National Oceanic and Atmospheric Administration (NOAA) that includes the National Ocean Service (NOS), which oversees the National Geodetic Survey (NGS) and Office of Aeronautical Charting agencies. The US Department of Agriculture has the US Geological Survey (USGS). All of these government cartographic organizations have worked closely to provide a coherent worldwide database to meet the needs of military and civil users in the US. In order to achieve complete, high-integrity terrain and obstacle databases for aeronautical SVS applications, it is likely necessary that a consortium of these agencies must make it their charter to develop such data. The burden to provide such capability is beyond the resources of any private corporation.

Table 4 summarizes some of the key sources of terrain data provided by some of these agencies.

Description	Database Density (Grid Spacing)	Horizontal Accuracy	Vertical Accuracy
1° Digital Terrain Elevation Data (Level 0)	1 km	50 m	30 m
1° Digital Terrain Elevation Data (Level 1)	100	50 m	30 m
1° Digital Terrain Elevation Data (Level 2)	30 m	50 m	30 m
1° US Geological Survey (USGS)	90 m	50 m	1 contour
15´ US Geological Survey	60 m	25 m	1 contour
7.5´ US Geological Survey	30 m	15 m	2 / 3 contour
7.5´ Digital Elevation Map (USGS)	30 m	13 m	14 m
Digital Elevation Map 1 Degree (USGS)	90 m	130 m	30 m
1° Digital Feature Analysis Data (Level 1)	1 km	130 m	10 m
Airport Safety Model Data (6 sq. radius nmi)	180 m	50 m	30 m
Airport Safety Model Data (50 sq. radius nmi)	450 m	50 m	30 m

Table 4 Terrain Data Sources

Geo-referenced database requirements are discussed in Section 2; a more detailed discussion of data availability and key issues concerning these databases is found in Section 3.

Synthetic Vision System (SVS) Cockpit Displays

Another critical enabling technology toward successful implementation of SVS applications are the SVS cockpit displays. These displays integrate the various aircraft information elements and SVS databases (i.e., aircraft position and state information, terrain / obstacles, weather, and traffic databases) for visual depiction of the outside environment to the flight crew.

A key consideration is the human factors associated with the optimum presentation of SVS information to the flight crew for each type of cockpit display. Cockpit displays such as the Primary Flight Display (PFD) and Head-Up Display (HUD) are typically used for tactical guidance by the flight crew. Navigation Displays (ND) / Multi-function Displays (MFD) are typically used for strategic situational awareness and planning by the flight crew. Other displays such as side-displays, weather radar displays, and standby indicator displays may also have a role for SVS.

Many combinations of information and display formats are being offered by the industry. At one end of the spectrum are information displays that are similar to conventional PFD and ND displays, using 2-D symbology depicting only pertinent situational awareness and guidance information as it relates to aircraft state, terrain, weather, and traffic. At the other end of the spectrum are displays that attempt to portray realistic images of the outside view using 3-D perspective view displays. Human factors studies must be conducted that determine the appropriate level of information integration and associated display formats that provide the proper mix and presentation of the outside environment to the flight crew. The information presentation and criticality of the SVS applications must be compatible. An overly realistic display of SVS data that has relatively low integrity (i.e., relatively high-probability for errors) can lead to use of this information for more critical strategic planning and / or tactical guidance by the flight crew, when the information itself cannot be trusted for such applications. Section 2.6.8 further discusses these issues and offers a range of SVS display types and formats that warrant consideration for future development of SVS displays. Note: Human factors study of SVS display information and formats is outside the scope of the contracted study.

A significant issue for incorporating SVS applications capability into the current aircraft fleet is the retrofit of SVS cockpit displays. This study indicates that retrofit of SVS cockpit displays is exceedingly difficult due to the limited graphics generation capability of older cockpits, and the considerably more demanding display processing requirements of SVS. Section 4 discusses aircraft retrofit issues for SVS applications.

Certification and Liability

The use of Synthetic Vision in the flight deck raises some important issues concerning the certification of SVS applications and also their liability. Key certification and liability issues are identified below. Section 5 provides a detailed discussion of certification and liability for SVS.

Key Issues Identified

This section examines Key Issues that are identified in the study. These issues identify critical areas of concern and needed analysis and concept development of SVS applications. These issues translate directly into Recommended Areas of Future Research and Development.

Key issues are presented for several categories: 1) SVS applications, 2) SVS databases, 3) aircraft retrofit, 4) SVS certification, and 5) SVS liability.

SVS Applications Issues

Application Enhancements

System enhancements may cause the criticality and thus the system integrity requirements of the system to increase. For example, if a 3-D PFD / HUD escape maneuver is added to a TAWS system, as a market discriminator, the system will become essential or critical.

Database Integrity Directly Affects the Application Integrity

A significant issue for SVS applications is the integrity associated with the SVS database. The SVS integrity is directly impacted by the integrity of the source data. If the source data has inadequate integrity (i.e., contains some undetected errors), then the SVS also has inadequate integrity.

High Integrity Databases for SVS Applications

Tactical SVS applications require very high system integrity. Due to the expected difficulty in achieving very high SVS database integrity, it may be necessary to have a second, completely independent, database to compare with the first. Since two completely independent sources for the required databases may not be feasible, other means may be required to corroborate the terrain databases. One possibility may be to use a ground-mapping mode of weather radar. Another possibility, near airports, may be to use a transponder based position determination system (either "ADS-B like", or multilateration based). The transponders would be located at strategic terrain locations to give a limited "picture" of the local terrain.

Applications Need To Know Integrity of Database in Real Time

SVS databases must indicate the level of integrity of the stored data. SVS applications may have to resort to a reduced level of operational performance, and some applications may not be available to the flight crew if data integrity is inadequate.

SVS Applications Have Significant Human Factors Considerations

There are many human factors issues that will need to be addressed for SVS. This report and the Literature Review in Appendix A raise many of these factors. The list below gives a sample of the human factors issues that will need to be addressed.

- What information is appropriate for display
- What combinations of information should be displayed / display modes
- What formats and graphical depictions are most appropriate
- Integration of various information sources for display purposes
  - SVS terrain / obstacles / cultural features / airport data / navigation data
  - Traffic information
  - Weather
  - Other information such as SUA, volcanic ash, data link messages, etc
- Strategic versus tactical versus safety / hazard display information depiction
  - Which displays for which information?
  - Information layering, level-of-detail needed, zoom levels, display modes
  - Display formats, type of depiction/rendering (2-D, 3-D other)

Reduced Separation Standards for Operational Benefits

The current IFR terrain separation standards were developed to allow for errors in terrain maps and also to account for typical aircraft navigation capability supported by current navigation aids. More airspace will be available for “free flight” if the separation standards can be reduce because of accurate terrain databases and aircraft SVS capabilities for strategic and tactical flight guidance. The safety of operations with reduced terrain separation standards needs to be investigated. If reduced terrain separation operations are deemed safe, the government regulations (FARs) will need to be revised.

Reduced Approach and Landing Minimums for Operational Benefits

The operational cost benefits and technical feasibility of the SVS approach applications requires further study. The reduced approach and landing minima limits for SVS, with and without, a head-up guidance system need to be established.

SVS can be used in the flight deck as an approach and landing aid to possibly reduce the need for airport lighting / signing / marking infrastructure.

Precision Approaches versus SVS

Since precision approaches are very safe and provide protection from CFIT and loss-of-control accidents. The role of SVS relative to the use of precision approaches needs to be evaluated. The benefit of SVS appears to be in blunder or emergency situations when the standard path was not or could not be followed, especially in terrain-difficult areas.

SVS Database Issues

Database Availability and Acquisition

There are many issues concerning the implementation and quality assurance of SVS databases. Top-level issues are as follows:

- The data to be derived from the Shuttle Mission is important for SVS databases because it is expected that this new data source will provide a much more accurate, resolute and affordable data set than is available today. The Shuttle Mission is for terrain data only. There is still a major issue with the generation and maintenance of a reliable worldwide obstacle data set.
- Terrain data, for the most part is available that will support applications in the enroute and approach / departure phases of flight.
- The Shuttle Mission is being relied on to provide a cost-effective terrain database to support the takeoff / landing operations.
- For the airport (i.e., surface operations) phase, it is expected that it will be some time before a global, cost effective and timely solution can be found to obtain a worldwide high-resolution / high-accuracy / high-integrity airport database solution. It is likely that for the near term, a selected set of airports can be mapped by using photogrammetry and GIS.
- A cost estimate summary for development / acquisition of SVS databases is summarized in Table 5 below. Total cost to develop this data is approximately ~$54.5 million.

SVS Terrain Database Flight Phase Requirement	Estimated Cost	Comment
Terrain for Departure / Approach phase (6-arc second data at not currently provided by Airport Safety Model Data (ASMD), vertical accuracy of 30 meters)	~$1000 per airport	~250 airports affected Note: If vertical accuracies better than 30 meters are required, use satellite imagery at ~$10,000 per airport (10 m vertical accuracy)
Terrain for Takeoff / Landing phase (6-arc second ASMD does not support vertical accuracy of 10 meters)	~$10,000 per airport	~450 airports affected Require satellite imagery to achieve vertical accuracy of 10 meters)
Satellite Imagery terrain for Takeoff / Landing phase (37 x 37 square kilometers)	$10,000 per airport	$50 million for 5,000 IFR airports worldwide
Airport database for Airport / Surface Operations	$30,000 per airport	Only Atlanta and Denver have been surveyed (requires photogrammetric techniques, conversion to vectors / GIS themes)

Table 5 Summary of Estimated Terrain Database Source Development Cost

General Database Issues

There are many issues that pertain to the SVS database. These are discussed to varying levels of detail in the report and are summarized here. The length of the issues list below signifies the importance of databases for SVS applications.

- Need for a rigorous process and standards in the development and use of SVS databases in avionics systems.

  RTCA DO-200A / EUROCAE ED-76 standards are current process standards for aviation databases. Due to the prospects for higher integrity requirements for SVS databases, industry must upgrade the current standards

  - Data source supplier(s) must develop and utilize several, independent, high-quality “truth” data sets for validation and integration into high-integrity databases for SVS use
  - Data distributor(s) that provide value-added data processing to SVS databases must follow a rigorous process to assure that they maintain the data integrity of the source providers. When integrating several sources of data, the distributor in essence becomes a source supplier of a new, integrated data set, that must follow a process similar to that of a data source supplier
  - SVS system developers, i.e., avionics manufactures, must follow a rigorous process in accepting and using SVS databases obtained from data source suppliers and data distributors, and are responsible for assuring SVS system integrity

    - The SVS end-user, i.e., airlines / pilots, are responsible to follow the process of data loading and updating integrity databases to ensure that system integrity is maintained. In addition, end-users must only use the SVS system in a manner consistent with the intended function / system integrity.

- Standard database message formats and data exchange standards for the various data types (grid posts, image data, geometric / vector data, etc) are needed.
    - Needed to contain / minimize cost of data handling, update and dissemination.
    - Needed to maintain integrity of database process.
- Current SVS data sets / databases are rather limited in integrity. Future applications will require expanded / additional validation of data to ensure higher database integrity.
- "Truth" data is needed in the development of high-integrity databases! How do we obtain "truth" data / what is acceptable "truth" data?
    - Very important for generation of high-integrity databases / validation of data.
- Terrain database issues
    - Enroute phase: Required grid resolution is in the range of 30 arc-seconds to 150 arc-seconds. Actual requirement depends on intended use. To support EGPWS / GCAS and current terrain separation standards, 150 arc-second data should be adequate. While not immediately available, 150 arc-second data can readily be obtained form available 30 arc-second data
    - Departure / Approach phase: For mountainous airports, Airport Safety Model Data (ASMD) with 15 arc-second grid spacing is not available for some non-US airports. There are ~250 mountainous airports for which ASMD data is not available
    - Takeoff / Landing phase: 6 arc-second ASMD data is available for all 100 US airports that are "terrain-challenged". Only 100 of 350 "terrain challenged" international airports outside the US are available

      In addition, ASMD data is only available at 30 m vertical accuracy. If this type of accuracy is inadequate for the takeoff / landing phase is needed, then all 5,000 IFR airports worldwide will require resurveying of terrain data. Satellite imagery data is likely required
    - Airport phase: Detailed survey of airports and conversion into GIS themes is estimated to cost $30,000 per airport. Only Atlanta Hartsfield and Denver International airports have been mapped to date.
- Obstacle database issues
    - Availability of accurate and reliable obstacle data is severely lacking, particularly outside the US
        - NIMA maintains a worldwide obstacle database of about 300,000 obstacles. These do not represent a complete database of obstacles and are only the tip of the iceberg
        - One must sweep all airports of obstacles before conducting high-integrity SVS applications / operations

- Enhanced development of a worldwide obstacle database is absolutely required for planned SVS applications. An effort through international standards organizations such as ICAO must be undertaken
- The Shuttle Mission will not provide reliable obstacle data. Obstacles may be evident for their latitude / longitude position, but will require resurvey to obtain accurate vertical accuracy
- Update of obstacle data is a significant issue. While terrain data is relatively static, obstacles can be erected in relatively short time. To maintain accurate and reliable updates of obstacle will require great vigilance and a reliable update process.

- Airport database availability
  - Requires local aerial photogrammetry that can survey the airports to 1-meter accuracy as required
  - It is expected to be a time-consuming and expensive undertaking to obtain an extensive set of airport data
  - New mapping technologies using photogrammetry and conversion into GIS are immerging, which may help reduce cost in the future.
- Cultural feature availability
  - Available cultural feature data cannot support the accuracy required around airports. Detailed airport cultural data will have to be derived from local aerial surveys.
- Release of high-resolution data: Due to the potential military use of high resolution terrain and obstacle data, there is a concern that governments may not make this data available for SVS users.
- Liability considerations concerning SVS databases
  - If high-integrity databases are the end-goal for SVS use, government and industry data providers must work together, using best commercial practices to reduce liability concerns, and stand behind their data.

Aircraft Retrofit Issues

<u>Only 34% of the Fleet is EFIS Equipped</u>

- Most EFIS equipped aircraft only have limited graphics capability available.
- Most graphics engines are only capable of the most elementary graphic elements.
- Existing display size: Most displays may not be large enough for SVS applications.
- Tactical applications are difficult to certify because tactical applications will affect the existing displays and drivers, which are certified to a critical level.
- Upgrade to an LCD may be necessary
  - If the display graphics engine and / or display need to be upgraded it may be easier and less costly to upgrade to a new system with an LCD and improved graphics capability.
- HUD and side displays may be alternatives for some aircraft.

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66% of the Fleet Have Electromechanical Instruments

- Old aircraft with electromechanical instruments cannot support SVS.
- Require replacing electromechanical instruments with state-of-the-art LCD displays capable of including SVS applications
  - 5 ATI LCD instruments are a retrofit candidate
  - Redo of flight deck instrument panel to install new displays that have a different form factor than the old displays is a serious cost factor.

Incorporation of Tactical SVS Applications Will Require Significant Aircraft Upgrades

- Capability of existing hardware is limited.
- Existing displays and display drivers need to be modified.
- HUDs may turn out to be a cost-effective way to introduce tactical SVS applications
  - HUDs enhance the operational capability
  - HUDs alleviate many human factors issues that are associated with adding new displays in an already crowded cockpit
  - HUDs may require less cockpit modification to install than new panel mounted displays.

Incorporation of Strategic SVS Applications May Be Less Costly

- Strategic SVS applications fall into the essential category.
- Retrofit of displays to support these applications may be less costly than strategic applications.
- Side displays may be suitable for strategic applications.

Incorporation of Tactical SVS Applications into A HUD

- May be more cost effective than display upgrades.
- HUDs do not affect certification of existing aircraft equipment.
- HUDs as add-ons do not affect operational procedures of existing systems which is significant training issue advantage.
- However, HUDs requires an inertial reference system which many older aircraft do not have.

SVS Certification Issues

- Currently, there are no standards defined for certifying SVS applications
  - No cognizant FAA organization has defined
  - Approvals will likely require use of equivalent safety
    - Exceptions to rules may need to be approved
    - Rule making effort may be required (may take 8 to 10 years to complete).
- Approval criteria are needed for end-to-end validation and verification, and quality assurance of SVS databases
  - RTCA documents, DO-200( ) and DO-201( ), are being defined to provide validation and verification plus quality assurance
  - The present documents do not provide adequate assurance of the quality of the data.

SVS Liability Issues

- Multiple parties are involved
  - Data source providers
  - Value added providers who integrated multiple data sources
  - Avionics manufactures and integrators
  - End users: airlines and pilots.
- Identification of liability responsibilities of various parties is required
  - As with TCAS approvals, the problem is to identify liability of participating parties
  - Need to get each participating party to accept appropriate level of liability.

Recommendations

The issues identified during this study are listed in above sections. Two major issues are identified by this study: 1) the lack of available high-integrity SVS databases, and 2) the difficult retrofit problem in integrating future SVS applications into the current aircraft fleet.

This study can serve as a starting point to address specific research topics, such as:

1) Refine the operational concept for specific SVS applications that offer the greatest potential benefits
   - Refine database accuracy, resolution and integrity requirements for these applications.
2) Resolve the numerous database related issues, especially those related to "database integrity" and "database process"
   - Develop an industry standard on how to achieve a certifiable, high-integrity SVS database
   - Develop an industry standard process for the handling and processing of SVS databases from data source provider to SVS end user

- Note: A consortium of US government data mapping agencies, FAA, and industry is likely required to provide high-integrity SVS databases.

3) Develop a synthetic vision applications roadmap and strategy for incremental retrofit to the existing fleet.
4) Develop certification standards for Synthetic Vision.
5) Conduct human factors studies to determine the appropriate type of information, information formats, and information presentation on synthetic vision displays.
6) Develop companion graphics generation capabilities for appropriate types of displays to support the display concepts that result from human factors investigation.

Preliminary System Requirements for Synthetic Vision

1.0 Introduction

This report documents the results of our study that addresses requirements and issues associated with the development of Synthetic Vision System (SVS) applications that provide safety and operational benefits to flight operations. This report examines top-level SVS applications that may provide safety and operational benefits. Since the cornerstone of SVS is the information database associated with terrain, obstacles and airport information, the focus of this report is on the requirements and issues associated with these databases in providing the needed SVS applications capabilities. This report also addresses avionics requirements and retrofit issues in providing SVS into the aircraft fleet. Also addressed are certification and liability issues associated with SVS.

The primary goal of this report is to identify potential SVS applications that may enhance safety and provide operational benefits and to determine top-level requirements and issues that must be considered in implementing SVS in avionics systems. SVS is addressed for both high-end air transport aircraft and also for small general aviation aircraft. In order to narrow the scope, this study does not address human factors associated with SVS display formats and information presentation to the pilot, which is left for further study in future NASA SVS research. In addition the study does not address the dynamic traffic and weather database components of SVS since these are also subjects in other NASA research programs. One such program is the NASA Aviation Weather Information (AWIN) program.

This study is the result of a cooperative effort between Rockwell Collins, Embry Riddle Aeronautical University (ERAU) and Jeppesen. ERAU focused on SVS requirements and issues associated with small general aviation end users. Jeppesen provided domain expertise in the area of databases (terrain, obstacle, airport and navigation databases). Rockwell Collins was the prime contractor of this study with focus on SVS applications high-end air transport, business and regional aircraft operators. The next section briefly identifies the scope and intended sub-tasks of this study.

1.1 NASA Synthetic Vision System (SVS) Study Tasks

The scope of this study is to characterize and document preliminary requirements and identify issues for a synthetic vision system (SVS) as well as for the associated databases and display systems as related to all phases of fixed wing aviation (general aviation and commercial aircraft). Potential applications for such a system would improve situational awareness for terrain awareness and warning, intuitive flight control guidance for navigation, and precision approach and landing capability in low visibility conditions. In addition, the study also identifies issues associated with retrofit, liability, certification and acquisition of data. Specific tasks addressed are as follows:

1) Identify and document potential marked applications for synthetic vision concepts. The concepts are to address both tactical and strategic display concepts and also address flight safety.

2) Document issues and technical challenges for developing a terrain database infrastructure to meet the potential market applications identified in step 1 above. Concepts will address both tactical and strategic display formats / concepts as well as acquiring, managing, and updating the data as necessary to support a navigational quality data base (terrain, obstacles, airports, etc.). Requirements to

consider include accuracy, resolution, level of detail, availability, human / display interface and form of data, compatibility of various data sources, update scenarios and integrity requirements.

3) Characterize display capability of existing aircraft in the fleet and address retrofit issues related to integration of SVS. Areas include various display types, display media capability, display generation capabilities, interfaces and capabilities of other required systems, e.g., navigation systems, etc.
4) Identify and characterize the potential liability issues that may arise with synthetic vision concepts. Compare this with how liability issues are handled today (e.g., TCAS).
5) Identify and characterize the potential issues associated with certification of a navigational quality SVS and the associated databases for safety (Terrain Awareness Warning System or TAWS) and precision approaches and landing guidance.

1.2 Organization of the report

The report is organized as follows: The remainder of Section 1 provides an overview of the current and future airspace system and examines the operational environments for both high-end airspace users (air transport, business and regional operators), and also small general aviation pilots. This discussion is provided to identify the potential role of SVS in providing safety and operational benefits. Section 2 discusses synthetic vision concepts, describes a generic synthetic vision system, and identifies potential SVS applications. Section 2 also provides top-level requirements for SVS subsystems based on the SVS applications. SVS database requirements and issues are the topic in Section 3. Section 4 examines SVS aircraft equipage and retrofit issues, while Section 5 addresses liability and certification consideration for SVS. Section 6 lists report references and Section 7 contains a table of acronyms. Appendix A contains a review of synthetic vision literature performed by ERAU. Appendix B discusses geodesy / datum issues.

1.3 Role of Synthetic Vision in Future Airspace System

1.3.1 Operational Environment Goals Overview

As indicated, the purpose of this study is to identify synthetic vision requirements and issues and their role in accident prevention / reduction, i.e., providing increased safety, and also to provide operational cost benefits. Before focusing on these topics, it is beneficial to examine the overall aircraft operational environment in order to put the use of synthetic vision technologies into the proper perspective. The following sections provide an overview of the current and planned air space system and operational environments and planned goals and initiatives to improve those operations. Both general aviation pilots and high-end air transport operators are considered.

1.3.2 Current Airspace System

The current airspace system has evolved over the last 50+ years and is predicated on a set of rules and regulations in conducting flight. These rules and regulations are intended to support safe operations. Aircraft conduct operations using either visual flight rules (VFR) or instrument flight rules (IFR). VFR operations are permissible when weather conditions are favorable, typically 3 miles visibility or greater and clear of clouds, and when aircraft operate outside positive controlled airspace. In VFR operations, pilots are fully responsible for the safe conduct of flight and use the outside visual scene to see-and-avoid other traffic, terrain and man-made obstacles. IFR flight rules apply to flight in lower-visibility weather and also when conducting flight operations in controlled airspace.

The current airspace system is built on the premise that Air Traffic Control (ATC) is responsible for tracking and providing separation assurance of participating traffic, providing control instructions / vectors to aircraft when needed to maintain adequate separation and proper traffic flow. Aircraft travel on predefined IFR air routes, TERPS, SIDS and STARS to ensure that aircraft are always under positive ATC control and are safe of hazardous terrain.

Communications, navigation, and surveillance (CNS) systems provide the necessary infrastructure and tools for ATC and pilots to achieve safe conduct of flight operations. These systems have evolved over time and are supplemented with well-defined procedures between ATC and pilots to support safe and efficient flight operations.

ATC utilizes primary and secondary surveillance radars to monitor and track aircraft. Voice radio communications are used between controllers and pilots to ensure proper spacing between aircraft, to provide vectoring instructions in the airport terminal area, and allow information exchanges necessary to conduct flight. Pilots utilize supplementary communications with flight information services and airline operations using voice and data link. Navigation aids such as VOR, DME, NDB, ILS, GPS, LORAN, and inertial systems allow flight crews to adequately navigate the IFR airways. Larger aircraft are also equipped with TCAS and GPWS as backup safety systems to prevent collisions with other aircraft or terrain in the event of failure of the airspace system.

The current airspace system has served the industry well and has an excellent safety record. However, continued growth in air travel is beginning to strain the system, resulting in increasing delays of operations at a significant cost to the industry. In addition, with the expected increases in air traffic, the current airspace system will experience relatively frequent accidents if current safety levels are not further improved. New technologies are becoming available that if utilized effectively are expected to provide an even greater level of safety, while at the same time allowing for increases in capacity. The NASA Aviation Safety Program has established goals to decrease the number of accidents by 80% within 10 years and by 90% in the next 20 years. It is expected that Synthetic Vision will be an important part in achieving these goals.

1.3.3 Future Airspace System

In response to the safety and capacity concerns noted above, the aviation industry has invested much effort and discussion on future enhancements to the current system to provide cost benefits in operations and increased safety. Concepts such as free flight, CNS / ATM (communications, navigation, surveillance air traffic management), and others rely on global, satellite-based navigation (GPS / Global Navigation Satellite System), global communications via data link and the Aeronautical Telecommunications Network (ATN), and Automatic Dependent Surveillance, both broadcast and addressed (ADS-B / ADS-A). In addition, advanced displays (for both ATC and the cockpit), ground-based and aircraft-based automation functions, increased availability of terrain databases, and greater capability information processing systems are expected to be the enabling technologies that allow improved safety and efficiency of flight to support future traffic demands.

It is expected that safety and capacity gains can only be achieved if a number of fundamental goals and objectives can be achieved based on the above noted technologies:

1) Greater sharing of timely aircraft position and intent information by all airspace participants using ADS-B.
2) Transparent communications between airspace participants via data link and ATN.
3) Reduced spacings between aircraft {e.g., Reduce Vertical Separation Minimums (RVSM), Required Navigation Performance {RNP}), supported by accurate, high integrity navigation systems.
4) Increasingly shared separation assurance responsibilities between ATC and flight crews, with primary means separation assurance responsibilities placed into the cockpit when in remote, uncontrolled areas.
5) Enhanced situational awareness for both controllers and flight crews in all weather conditions. For the flight deck, this entails an accurate and reliable depiction of traffic, weather, terrain, airport taxi routes, special use airspace (SUA), etc., information relative to current aircraft position and intended flight plan. This information may be used for the purposes of a safety / hazard system(s) and also for strategic / tactical guidance. The synthetic vision system (SVS), which is the focus of this report, will play an important role in this area.

The above capabilities support a more flexible routing system that allows aircraft to make use of minimum distance / favorable wind routes for time and fuel savings, and also permits closer aircraft spacings for increased terminal area throughput / capacity.

The challenges for the industry are on how to evolve effectively toward these future capabilities, while 1) keeping in mind the realities of a protracted transition period of both new and older aircraft equipage / capabilities; 2) diversity in airspace users, i.e., small general aviation aircraft versus high-end air transports; and 3) diversity in the airspace itself, ranging from high-end ATC systems in populated areas in the US and Western Europe to relatively little ATC infrastructure / capabilities in remote areas. The following sections briefly examine the operational environments of general aviation and higher-end air transport users to note the unique requirements of these users, in order to set the stage for discussion of SVS issues and requirements.

1.3.4 Operational Environment for high-end Air Transport Operators

Air transport, business and regional operators are motivated by the economics of moving people from place to place in a safe, timely and comfortable manner, while maintaining efficiency in their operations. These operators are typically equipped with the appropriate level of advanced CNS and flight deck avionics that provide the needed capability to conduct IFR operations to the weather minima that are commensurate with their regions of operation. These users typically are long-haul operators and thus utilize high-altitude routes for efficient flight operations. Typical flight deck displays for these operators are the primary flight displays (PFDs) and navigation / multifunction displays (NDs / MFDs) that provide aircraft attitude, state and flight plan information using conventional display formats standardized by the industry. Other cockpit displays on current aircraft are standby attitude indicator displays, weather radar and TCAS displays for display of weather radar and traffic information, and when justifiable by operational benefits, head-up displays (HUDs) for tactical guidance information that allows operations to lower weather minima.

These operators have already been experiencing additional cost burdens in their operations due to higher user fees, and the increasing cost of delays due to the lack of capacity of the airspace system, particularly during adverse weather. As traffic demand continues to increase, delay problems and cost of operations will continue to worsen until new airspace and aircraft capabilities can be implemented.

From an SVS perspective, these operators require or can benefit from the following capabilities as part of the transition to the future airspace system in order to improve operations:

1) Separation assurance capability from other traffic (i.e., ADS-B based separation assurance applications) supported by automation systems and also cockpit display of traffic information (CDTI). This capability is needed to support closer separation standards to facilitate flexible routing for greater capacity.

2) Weather information in the cockpit that allows wide area weather information to be data linked to the aircraft to support situational awareness of threatening weather and to support flexible routing and flight path replanning needed to support the airspace system of the future. The NASA Aviation Weather Information (AWIN) program is studying this topic.

3) Capability to depict terrain, obstacles and possibly cultural features for situational awareness and terrain / obstacle avoidance. Again this capability is needed to support flexible routing and flight path replanning. Due to the typical high-altitude enroute flight paths for these operators, terrain and obstacle data take on added significance primarily during terminal area, landing and takeoff phases of flight and is expected to be an important aspect of CFIT and loss-of-control accident prevention.

   In addition, to increase airport surface operational capacity and safety, accurate airport databases are needed to support depiction of the surface traffic situation, taxi routes and runway incursion protection information (to both the flight deck and controllers).

4) An accurate navigation system that supports relatively narrow containment tunnels, also referred to as Required Navigation Performance (RNP), e.g., RNP<1 nmi. RNP indicates that an aircraft's available navigation system can maintain the aircraft within the prescribed tunnel dimensions with a high degree of integrity. RNP implies accurate positioning and flight path maintenance which is vital to accurate depiction of other SVS databases such as traffic, weather, terrain / obstacles and the airport layout. Also, electronic display of navigation database information and depiction of the active aircraft flight plan is closely associated with RNP and SVS.

The above SVS capabilities / applications may be utilized strictly to support safety / hazard warning systems. These types of systems are primarily "safety belt systems" that are used as a last resort in the event of failure of other systems. At this point it is important to note that safety / hazard warning systems typically do not require high-levels of system integrity. While this may seem counterintuitive, safety systems back up other strategic and tactical systems, which already have relatively high system integrity requirements. Safety / hazard warning systems provide additional protection against system failures for these higher integrity systems, but typically only require relatively low system integrity. (An overview of integrity / criticality categories for the various SVS applications is discussed in section 2).

SVS capabilities / applications can also be used for strategic and tactical guidance information to the flight crew. For these SVS applications, system integrity becomes more critical and imposes greater integrity / quality requirements on the information databases that are used in such systems.

Note: A high-integrity information system implies that there is a low probability of misleading information being presented to the pilot. Conversely, a low-integrity system allows a greater possibility that misleading information may be present in the system. Integrity is often erroneously confused with data accuracy / resolution.

One of the fundamental challenges in incorporating SVS capabilities pertains to the display of SVS database information on cockpit displays. As indicated earlier, current aircraft displays use conventional display formats that are primarily limited to PFD and ND symbology. In addition, a wide range of aircraft display capability is currently present in the aircraft fleet, ranging from the classic aircraft, which utilize mechanical, round-dial displays for guidance, to glass cockpits using CRT stroke-type displays, to LCD displays on new aircraft. Depending on the SVS capability / application being sought, and the final human-factors developed display formats needed for the respective SVS capability / application, SVS display requirements will be considerably greater in terms of graphics generation, stroke and raster display capability compared to conventional cockpit displays. Thus a significant SVS displays retrofit issue exists. For new aircraft, new SVS capable display technology is becoming viable, far exceeding the capabilities of current displays.

It is interesting to note the contrast between general aviation and high-end air transports as it pertains to cockpit display of SVS information. Rapid advancements in processor, database and graphics generation technology have spawned many potential display concepts for general aviation use, allowing for potentially rapid product insertion into the general aviation aircraft cockpit, e.g., such as 3-D terrain displays. For air transport aircraft, this process is much slower. High-end air transports require development of high-integrity systems that have significant certification costs associated with them compared to general aviation systems. In addition, display formats for PFD and ND display formats have been very stable and have been in use for a long time for air transport, business and regional operators. Format changes are usually slow to occur in this area. While the LCD technology itself is very advanced for these aircraft types, the development of sophisticated 3-D display graphics generation has not kept pace due to the constrained display formats and also due to high certification costs that encourage simplicity in display generation design (both hardware and software).

Whether for retrofit or for new aircraft, SVS technologies / subsystems affect many aspects of the overall avionics system. SVS is closely coupled to the other components of the avionics system, e.g., the aircraft information processing subsystem and the display subsystem, and careful consideration must be given to how SVS is integrated in a cost-effective manner. Primary issues in successfully implementing SVS will be the cost and certification requirements associated with these new SVS cockpit displays and associated databases. These display and database issues will be addressed later in this report.

1.3.5 Operational Environment for General Aviation Pilots

The operational environment and associated operational requirements are more diverse for the general aviation pilot community when compared to high-end air transport users. This is primarily due to the wide uses of general aviation flight. While a large population of general aviation pilots fly simply for recreational purposes and many fly only in VFR conditions, there are also a diverse number of flights conducted for business purposes (single day trips, company flight operations, aircraft rental, charter and air taxi operations, and leased transportation services). This diversity in operational uses and the range of pilot capabilities (in terms of VFR and IFR ratings) impose special considerations and airspace system needs for general aviation.

As indicated, general aviation flights often are conducted in VFR conditions, allowing the pilot the freedom for free flight as long as he remains outside of positive controlled airspace. For this pilot, the cost of operating his aircraft is of fundamental concern, since he is directly paying for the “joy of flying” and cannot afford it if costs are excessive. Of course, even for general aviation pilots that conduct IFR operations (thus requiring additional avionics systems capability and pilot training), low cost is a primary consideration. Any requirements for additional avionics capability must provide sufficient cost benefits before it will be accepted by the general aviation community.

Similar to air transport operations, general aviation IFR flight operations require filing of a flight plan and are supported by ATC to ensure proper airspace management and separation assurance. Unlike air transport pilots, who are aided by the support system provided via airline operational communications (AOC) to airline dispatch, general aviation pilots often rely on obtaining flight information services and pre-departure weather briefing on their own in planning and conducting their flight.

Since general aviation aircraft typically fly lower-altitude routes, they also are considerably more vulnerable to inclement weather conditions, such as precipitation and especially icing, by not being able to over-fly the adverse weather like their air transport counterparts. Thus general aviation pilots, more than their air transport counterparts, can benefit from improved information in the cockpit pertaining to weather. Terrain information is also very important to the general aviation pilot due to the relatively close proximity of operations to terrain. This is especially true in mountainous areas because the terrain height may exceed the service ceiling of the aircraft. Similarly, for traffic, air transport operators are equipped with TCAS that provides an indication of proximate traffic and warnings against potential traffic conflicts. General aviation pilots can greatly benefit from traffic information derived from ADS-B and uplink of traffic information via data link (Traffic Information Services broadcast – TIS-B) for separation assurance.

The rapid advancements in technology (processors, software, open systems standardization, information / database processing systems, LCD displays and display generation, etc.) have enabled many innovative companies to develop exciting and sophisticated technologies for general aviation use. In fact, these rapid technology developments for general aviation are in some ways outpacing the infusion of technology into the high-end air transport aircraft, especially in the area of sophisticated 2-D / 3-D aircraft display and graphics generation technologies. A general aviation pilot can have a sophisticated 3-D terrain display in his cockpit via a laptop computer as long as it is only providing supplemental (not required) information. The NASA Advanced General Aviation Technology Experiment (AGATE) program is developing technologies to put the sophisticated 2-D / 3-D display capability into the general aviation instrument panel. Due to the small size of general aviation aircraft all necessary information needs to be displayed on a single display. There will be a second display for reversionary purposes in case the first display fails. Until it is required for reversionary purposes, the second display can be used to display auxiliary information.

As indicated earlier, the general aviation pilot can use much assistance / information in the cockpit to greatly improve his operational environment. The NASA Advanced General Aviation Transport Experiments (AGATE) program is attempting to leverage these advanced technologies to reenergize the general aviation market by developing a low-cost aircraft that is relatively easy to fly in near all-weather conditions. Cockpit decision aids and decision support systems play an important part in achieving this goal.

It is clear that general aviation pilots can benefit significantly from a synthetic vision system (SVS). An SVS that provides situational awareness and perhaps also guidance information with respect to terrain proximity, weather and traffic is fundamental to improving the operational environment for this community. The challenge is to provide SVS capability that is cost-effective (both avionics cost and certification cost) to the general aviation user.

This report will address SVS issues and requirements as they pertain to both, general aviation pilots and air transport, business and regional operators.

2.0 Synthetic Vision System Application Concepts

Collins with significant participation by Embry Riddle Aeronautical University (ERAU) applied a systems engineering approach to defining a synthetic vision system. Using this approach it was realized that synthetic vision is only a subset of the information a pilot needs to fly the aircraft. Since the synthetic vision information needs to be displayed along with other data, the Collins / ERAU team tried to consider the synthetic vision information in context with the other information the pilot needs. Collins addressed this issue for the high-end user represented by air transport, business, and regional operators. As a starting point it was assumed that basic flight information is already available to the pilot and that SVS features may be added for retrofit to existing avionics architectures or as a new avionics capability. ERAU addressed the general aviation market from an AGATE perspective where new flight deck design philosophies are being considered. Consistent with the AGATE perspective, ERAU conducted a requirements analysis of the general aviation flight deck. The details of the ERAU analysis are documented in an unpublished ERAU report titled “NASA Synthetic Vision: Requirements Analysis and High Level Functions,” (ERAU November 15, 1998). Many of the requirements in the ERAU report are broader than synthetic vision requirements. The pertinent synthetic vision requirements from this ERAU analysis are included in this report.

In the context of this report, the term Synthetic Vision System (SVS) refers to any avionics system that utilizes database information of the outside world and current position information to provide the flight crew with situational awareness information. This situational awareness information may be depicted on one or more of the cockpit displays. Typical SVS databases include the following:

- Terrain data
- Obstacle data
- Cultural features
- Weather information
- Traffic information

Per the contract statement of work, the scope of this study addresses only the geo-referenced databases, i.e., terrain data, obstacle data, cultural features, and related databases such as airport and navigation databases. While also fundamental to SVS, wide area weather information that is typically data linked from ground stations, and traffic information derived from ADS-B or other surveillance / data link systems are not included in this study. Weather is already being addressed in NASA Aviation Weather Information (AWIN) studies and traffic encompasses another set of technology issues that are not the focus of this study. Nevertheless, an overall SVS system would integrate all of these aviation databases into the flight deck, providing the flight crew with situational awareness about their environment. SVS as defined above does not include systems that use on-aircraft “vision” sensors, i.e., sensors that supplement what the pilots can see visually, or sensors such as infrared, millimeter wave radar, video, weather radar, etc. Thus wide area weather is viewed as a dynamic database that is maintained by a ground system and is then uplinked to the aircraft via data link, while weather radar data is viewed as coming from the enhanced vision sensors.

Summarizing, this study focuses on the relatively static, geo-referenced SVS databases. Future NASA studies will address integration of these databases with dynamic weather databases (from AWIN research) and also dynamic traffic database information.

The remainder of Section 2.0 is organized as follows: Section 2.1 describes the components of a generic synthetic vision system (SVS). Section 2.2 briefly identifies the NASA Aviation Safety Program and the motivation for SVS developments / studies. Sections 2.3 and 2.4 provide a review of CFIT and loss-of-control accidents, identify associated accident causal factors, and indicate top-level SVS information requirements to reduce and eliminate these accidents. Section 2.5 then overviews the generic SVS application categories of safety, strategic and tactical applications. Section 2.5 also examines candidate SVS applications that may provide benefits of improved safety and / or operational benefits. Section 2.6 then allocates SVS requirements to the individual SVS sub-systems. Section 2.7 summarizes the key issues for the SVS applications identified in Section 2.

2.1 Generic Synthetic Vision System

Figure 2-1 contains a context diagram of a generic synthetic vision system. As indicated, while uplinked weather and traffic databases are part of a complete synthetic vision system, they are shown in gray to indicate that they are not considered further in this report. In addition, while vision sensors are not considered part of a synthetic vision system, vision sensors are included in the diagram to indicate that many functions are common to synthetic vision and enhanced vision systems.

The intent of the diagram in Figure 2-1 is to illustrate some of the functions required for synthetic vision. The diagram is not intended to imply a specific system implementation or system architecture. The key functions of SVS are:

- Geo-referenced databases
- Position information
- Aircraft state information
- SVS applications processing
- Graphics rendering / display manager / image fusion
- Display media

SVS has many components in common with the other avionics systems. The aircraft state sensors and position information are used by many systems. Selected elements of the geo-referenced databases (e.g., navigation aids) are use by the navigation system. The display system represented by the graphics rendering / display manager / image fusion and the displays are shared with other existing systems such as navigation and flight control.

SVS specific components are SVS applications processing and some elements of the geo-referenced databases. SVS applications processing may be implemented in a dedicated computing component or it may share the computing component of another system.

The NASA Aviation Safety Program, in partnership with the FAA and the aerospace industry will provide the research and technology products needed to help the FAA and the aerospace industry to improve aviation safety: 1) five-fold over the next 10 years, and 2) ten-fold improvement over the next 20 years.

The Single Aircraft Accident Prevention (SAAP) initiative is one of several programs under the NASA Aviation Safety Program Office working to achieve the improved safety goal. The NASA Langley Research Center Implementation Plan (NASA 1998) lists the goals and objectives of the various research activities for 1999. The safety initiatives that incorporate synthetic vision are summarized below.

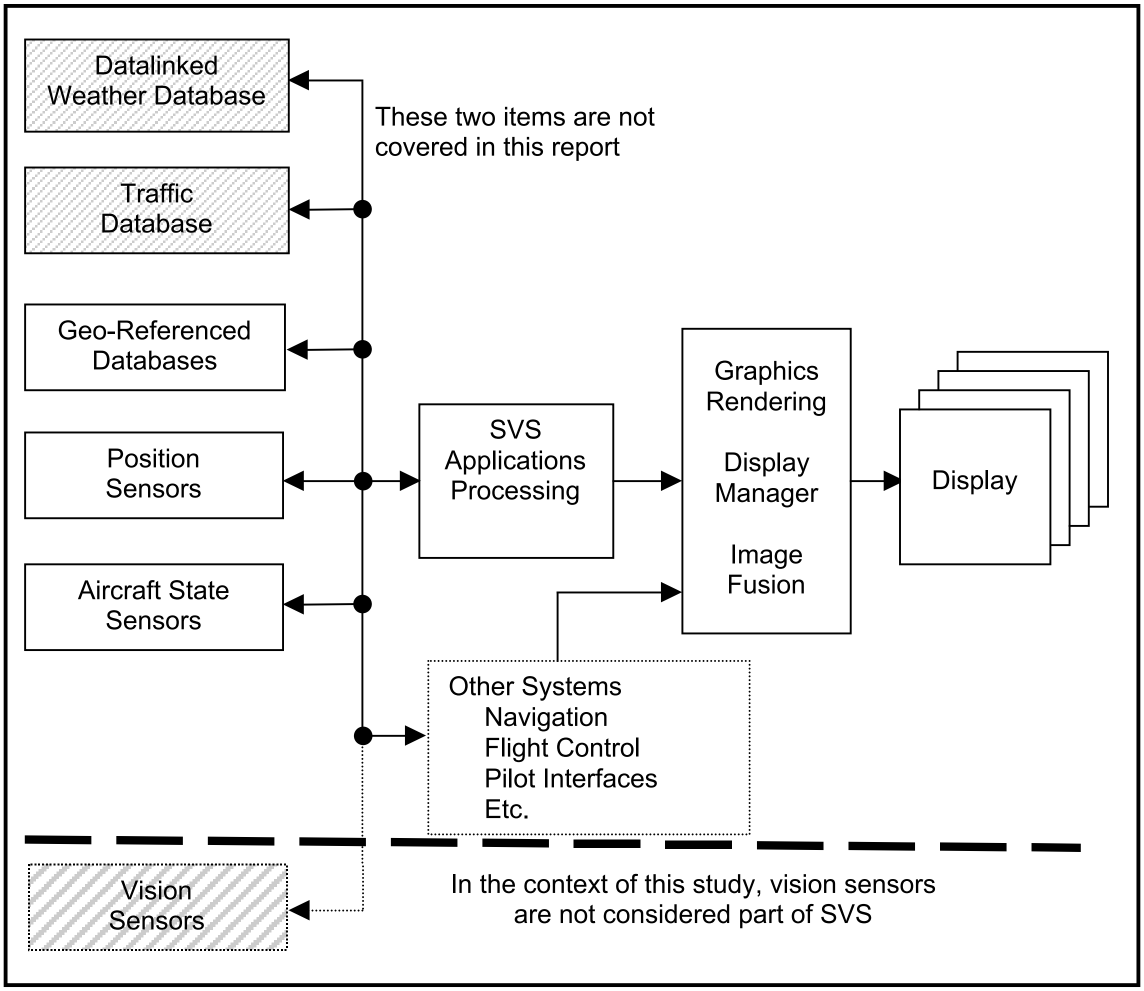


Figure 2-1 Generic Synthetic Vision System (SVS)

2.2 Synthetic Vision for Enhancement to Safety

The goal of SAAP is to develop and support implementation of technologies that go onboard aircraft or have airborne applications that will reduce the fatal accident rate. The goals of SAAP that relate to this study are:

- Complete certification plans and flight deck requirements for Synthetic Vision Precision Approach and Landing (PAL) systems onboard an aircraft.
- Complete flight demonstration and provide documentation to support feasibility and certification criteria of synthetic vision display systems for eliminating low-visibility induced general aviation accidents.
- Complete flight demonstration of Integrated Transport synthetic vision display for eliminating low-visibility induced accidents.

- Enable implementation of standardized format for worldwide terrain and airport database information.

2.3 Review of CFIT and Loss-of-Control Accidents

One of the important benefits of SVS is to provide the flight crew with enhanced situational awareness by providing synthetic vision information cues in the flight deck to compensate for operations in difficult visibility conditions, i.e., operations in low-visibility weather, whiteout and black night conditions. Thus, SVS can play an important role in accident prevention and improved safety of operations.

In order to determine requirements of SVS that can provide safety benefits one must first investigate previous aviation accidents and their causal factors. Knowledge of the root causes of accidents can determine the type of information and its flight deck presentation to the flight crew that ensures appropriate situational awareness and guidance to the flight crew to prevent the occurrence of certain types of accidents. While the scope of this study did not warrant an in depth study of accident cases, we reviewed the results of a number of accident studies to assess root causes and information deficiencies that caused the accident.

The accident categories used in this report are taken from the “Aviation Safety Program Element Traceability Database Report” (Aviation Research, Inc. 1998). This is done in order to maintain consistent terminology across the various safety projects being conducted by NASA. The accident categories are summarized below:

- Controlled Flight into Terrain (CFIT)
- Aircraft Control (Loss-of-Control)
- Icing
- System / Component Failure
- Ground Handling
- Runway Incursion Collisions
- Mid-Air Collisions
- Ground Collisions
- In-flight Fuel Related
- Fire In-flight
- Unknown

SVS cannot provide a direct benefit for all of the accident categories listed above. It can, however, be of significant benefit for CFIT, Loss-of-Control and Runway Incursions. The Runway Incursion problem is being addressed by other NASA initiatives and thus is not covered in this report. The focuse of this report is on CFIT and Loss-of-Control accidents, and how SVS can provide significant benefits in reducing and eliminating the occurrence of such incidents.

The referenced report (Aviation Research, Inc. 1998) provides a definition of each of the listed accident categories. The report’s definitions for CFIT and Loss-of-Control are listed below to aid in clarifying the meaning of these terms.

Controlled Flight into Terrain (CFIT)

CFIT is the type of accident in which the aircraft had not experienced a failure / malfunction and the flight crew were not incapacitated. These types of accident are non-upset, non-loss-of-control related and cover all phases of flight except for descent-below-minimums. Accidents due to descent-below-minimums are classified in a separate category. Thus, CFIT accidents typically involve flight of a properly operating aircraft into ground impact without the flight crew having the situational awareness of realize the seriousness of the situation.

Aircraft Control (Loss-of-Control)

These types of accidents entail aircrew induced upset or loss-of-control in 1) visual flight conditions and include all upsets / loss-of-control where outside visual reference was not restricted, and 2) operations in Instrument Meteorological Conditions (IMC), night or other vision restrictions, e.g., whiteout, glare, fog, clouds, haze, etc. Inadvertent transition from VFR to IMC conditions and “scud-running” (i.e., ducking under restricted visibility weather conditions) induced upset / loss-of-control; and spatial disorientation accidents also fall into this category.

CFIT and Loss-of-Control accidents have cause the greatest number of fatalities over the last ten years (Dornhiem 1998). Making a reduction of accidents in these categories will have a significant impact on the overall accident rate.

2.4 Accident Causal Factors

The UK CAA Accident Analysis Group has developed a standardized list of accident causal factors and this same list is being used by the Flight Safety Foundation in an approach and landing accident study (Khatwa 1997). The main accident causal factor groups are:

- Aircraft
- ATC / Ground Aids
- Environment
- Flight Crew
- Maintenance / Ground Handling
- Design
- Infrastructure (Company and Regulation)

In reviewing these causal factors it is obvious that SVS can provide the most benefit for accident that are caused by crew factors. SVS may prove useful in mitigating the effects of some of the other causes. For example, a terrain display may help a flight crew find an alternate landing site when there is an aircraft component failure or when the environment (weather, icing, etc.) causes the need to deviate from the planned route.

2.4.1 CFIT Accidents

A study of 156 fatal CFIT accidents that occurred in the 1988 - 1994 timeframe (Khatwa and Roelen 1996) (Khatwa and Roelen 1997) identified several crew errors as the dominate causes of the accidents studied. The percentages listed below are the percentages of times that a specific error was found to be one of the causes of an accident. More than one factor may have contributed to an accident so the total percentages will add up to more than 100%. The three largest categories of errors listed in that report are:

- Situational awareness [loss of vertical and / or lateral spatial awareness] (44.9%)
- Tactical decision making (44.2%)
- Procedural (34%)

One of the report's conclusions is that improved terrain situational awareness should be encouraged. The report recommends "technological developments that give to the flight crew a visual display of terrain."

In a CFIT study of general aviation aircraft (Bud, et al 1997), a similar conclusion was reached. That report concluded "Moving maps with terrain displays may provide a way to better orient GA pilots in low-visibility situations: electronic moving map displays may alert the pilots to avoid accidents before they occur."

Two CFIT accident types are worthy of special note because they are of significance to general aviation operations. These are CFIT accidents that happen during non-precision approaches (NPA) and accidents that happen after inadvertent flight from visual meteorological conditions (VMC) into instrument meteorological conditions (IMC).

The Khatwa and Roelen CFIT accident study referenced above showed that almost 60 percent of the approach and landing CFIT accidents involved aircraft flying non precision approaches. In addition, 40 percent of the total landing and decent accidents occurred where significant terrain features were not present. This indicates that CFIT accidents do occur in areas without high terrain. Although not included in the study, anecdotal reports have indicated that while both vertical and lateral spatial awareness (or lack thereof) play a role in NPA CFIT accidents, the predominant problem is vertical spatial awareness.

This same study found that 19% of the CFIT accidents included in the study involved inadvertent VMC flight into IMC conditions. Most of these accidents occurred under single pilot operations.

2.4.2 Loss-of-Control Accidents

Although loss-of-control is usually listed as the second largest category of accidents, there is not a consensus as to which accidents should be included in this category (Dornheim 1998). For example, should the A320 flyby crash at Mulhouse-Habsheim be considered a loss of control accident since the pilot was purposely flying slow and low to the ground?

Many loss-of-control conditions have occurred after a known mechanical failure that compromised control, possibly in an uncontrollable manner. It is not clear how SVS could be beneficial in preventing, or in assisting in the recovery from, these types of loss-of-control accidents.

SVS should be beneficial in preventing loss-of-control that sometimes results during dark night / whiteout conditions. Basic attitude information should be sufficient to prevent loss-of-control under dark night / whiteout conditions but loss-of-control accidents still occur in these conditions. The SVS terrain display could act as a reinforcement of the basic attitude information displayed in the aircraft. Pathway-in-the-sky display formats could also be beneficial for these conditions. In context of this report, a pathway display format is considered a SVS application. A pathway display uses a navigational database and current aircraft position to synthesize the pathway. When used in this manner the SVS is being used as a tactical system.

In an indirect manner, SVS (terrain and / or pathway) can provide additional situational awareness information that may be of assistance to the flight crew once a loss-of-control situation has developed.

2.5 Synthetic Vision Applications Categories

This Section examines SVS applications categories. As will be addressed later in this section, SVS may be utilized to provide a range of safety and operational benefits. While there may be a wide range of SVS applications, it is useful to group them into more general categories that facilitate development of SVS top-level requirements. One way to map SVS applications into categories is to map them according to levels of system criticality, where system criticality refers to “the extent of effects on aircraft and occupants in the event of a system failure”. The criticality of a system has a major impact on system requirements.

In this report SVS applications are placed into the following categories: 1) SVS safety system applications, 2) SVS strategic applications, and 3) SVS tactical applications. Before each of these categories is examined individually, the next section gives a brief overview of how the aviation industry classifies system functions with respect to “Effects Categories” in the event of a system failure.

2.5.1 Avionics Systems - Effects Categories

“Effects categories” are shown in Figure 2-2. From Figure 2-2, “effects categories” indicate the impact of a system failure to the flight crew / aircraft and occupants. Effects range from “minor” to “catastrophic”. “Minor” effects are those that result in only slight increases in crew workload and / or in some inconvenience to some of the occupants. “Catastrophic” effects are those that result in a prevention of continued safe flight, resulting in deaths and probable loss of aircraft. The classifications of minor, major, hazardous, and catastrophic have associated with them some qualitative and quantitative terms related to system criticality and the probability of failure events. Systems are typically assigned a criticality category and are thus referred to as being non-essential, essential or critical systems. Associated with these terms are probability of occurrence rates of failure events ranging from 10^{-3} to 10^{-9} or less. Also tied to these categories are software certification requirements that are provided in RTCA DO-178B, which classifies software by levels, A to D, with level A representing critical software. Development of level A software must follow stringent standards to provide assurance of high software / system integrity.

Before new avionics systems are developed and introduced for operational use, an assessment is made of the expected criticality of the system and the required level of system integrity. These assessments are made on a case-by-case basis for each avionics system. For the purpose of this report, SVS applications categories are generally assumed to have the following effects and integrity classifications:

1) SVS Safety System Applications

   From the perspective of the effects categories (Figure 2-2), SVS safety system applications are viewed to be “non-essential”. The integrity level of these applications are $\sim 10^{-5}$, indicating that the probability of an unannunciated loss of the safety function (e.g., terrain warning function) are greater than or equal to 10^{-5}. Categorizing a “safety” system as “non-essential”, requiring only a low-level of integrity may seem somewhat counterintuitive. However, since safety systems are only back-up systems, inadvertent loss-of-function for these systems has only minor impact on aircraft operations, thus the low integrity requirement.

Effect On Aircraft And Occupants (AC 25.1309-1A)	Slight reduction in safety margins. Slight increase in workload. Inconvenience to occupants.	Significant reduction in safety margins. Difficult for crew to cope with adverse conditions. Passenger injuries	Large reduction in safety margins. Crew extended because of workload or environmental conditions. Serious injury or death of small number of occupants.	Prevention of continued safe flight. Multiple deaths, usually with loss of aircraft.
Effects Category (AC 25.1309-1A)	MINOR	MAJOR	HAZARDOUS	CATASTROPHIC
Software Level RTCA DO-178B	LEVEL D	LEVEL C	LEVEL B	LEVEL A
Criticality (AC 25.1309-1A)	NON-ESSENTIAL	ESSENTIAL		CRITICAL
Qualitative Probability (FAR 25)	PROBABLE	IMPROBABLE		EXTREMELY IMPROBABLE
Qualitative Probability (JAR 25)	REASONABLY PROBABLE	REMOTE	EXTREMELY REMOTE	EXTREMELY IMPROBABLE

10^{-3} 10^{-5} 10^{-7} 10^{-9}

PROBABILITY OF EVENT PER HOUR

Figure 2-2 Effects Categories – Failure Probabilities versus Severity of Effects

2) SVS Strategic Applications

   SVS strategic applications are viewed to be “essential” from an effects category perspective. Integrity for these types of SVS applications is on the order of 10^{-5} to 10^{-9} (typically $\sim10^{-7}$).

3) SVS Tactical Applications

   SVS tactical applications, being closely associated with providing guidance cues to the flight crew, are expected to be “critical” systems with integrity levels of less than or equal to $\sim10^{-9}$.

As indicated, criticality of a system is closely associated with system integrity. A highly critical system must have high integrity associated with it, where integrity provides an indication of system quality. A high integrity system must have a low probability of occurrence of inadvertent, misleading / inaccurate information that can adversely affect system function. To achieve high integrity systems often requires use of redundant systems, and high-levels of system monitoring in order to detect system failures. Depending on the type of application, a major issue for SVS is the integrity of the databases needed to assure overall system integrity. Integrity is especially critical for SVS tactical applications that provide guidance information based on terrain database information. The SVS database integrity issue is discussed later in Section 3. The next sections describe each of the SVS applications categories.

Note: This report intentionally uses the term "SVS **safety system** applications" to emphasize that these types of applications are intended only as backup systems, i.e., applications that provide hazard warnings as safety belt systems or systems of last resort. These types of applications fall under the category of "non-essential" and have relatively low system integrity ($\sim 10^{-5}$). <u>SVS strategic and SVS tactical applications also provide safety benefits</u> but fall into different criticality categories with higher system integrity.

2.5.2 SVS Safety System Applications

An SVS system utilizes databases to support the flight crew with situational awareness of traffic, weather, and terrain / obstacles. SVS safety system applications currently in use are 1) Traffic Alert and Collision Avoidance System (TCAS) for traffic collision avoidance, 2) weather radar and windshear alerting systems for detection of adverse weather, and 3) Ground Proximity Warning System (GPWS) to warn against flight into terrain. The focus of this study is on synthetic vision relating to flight in the proximity to terrain, and thus only SVS safety applications pertaining to terrain warning are considered here.

2.5.2.1 GPWS

GPWS has been the terrain warning system used by the US major and commuter airline fleet for many years and has provided safety benefits to prevent CFIT. However, due to lack of a terrain database, GPWS is primarily a look-down system in sensing terrain and is thus a less than optimum terrain hazard detection system. It's inability to adequately project the future aircraft track relative to the terrain results in many false alarms. In addition, during approach / landing, GPWS is disabled once the aircraft is properly configured in order to eliminate false alarms. Thus GPWS provides only minimal CFIT safety benefits during approach / landing operations, where CFIT is a serious concern.

2.5.2.2 EGPWS

Enhanced GPWS (EGPWS) provides significant improvement over GPWS due to the use of terrain database information. This allows EGPWS to provide a forward looking terrain avoidance capability versus the look-down capability of GPWS. Using the terrain data and forward looking trajectory prediction, EGPWS has improved alerting capability (i.e., greater probability of correctly detecting a terrain hazard with a reduced number of false alarms). In addition to providing the basic GPWS modes (with improved alerting), EGPWS also provides additional modes that provide improved warning during approach / landing using a terrain clearance floor to assure terrain separation.

As stated, with the terrain database and forward looking trajectory prediction, EGPWS provides improved alerting. This includes greater caution and warning times that allow additional time for the flight crew to assess the situation and take appropriate evasive maneuvers. It should be noted that EGPWS does not factor in an evasive maneuver into the alerting algorithm, but instead attempts to maximize caution and warning times.

Another capability of EGPWS versus GPWS is the addition of a terrain display that depicts terrain relative to aircraft position. The display provides an indication of the level of hazard of surrounding terrain by using color-coded shading of terrain data (red, yellow and green). Figure 2-3 shows a typical EGPWS terrain display, which is a 2-D plan view of terrain on a weather radar display.

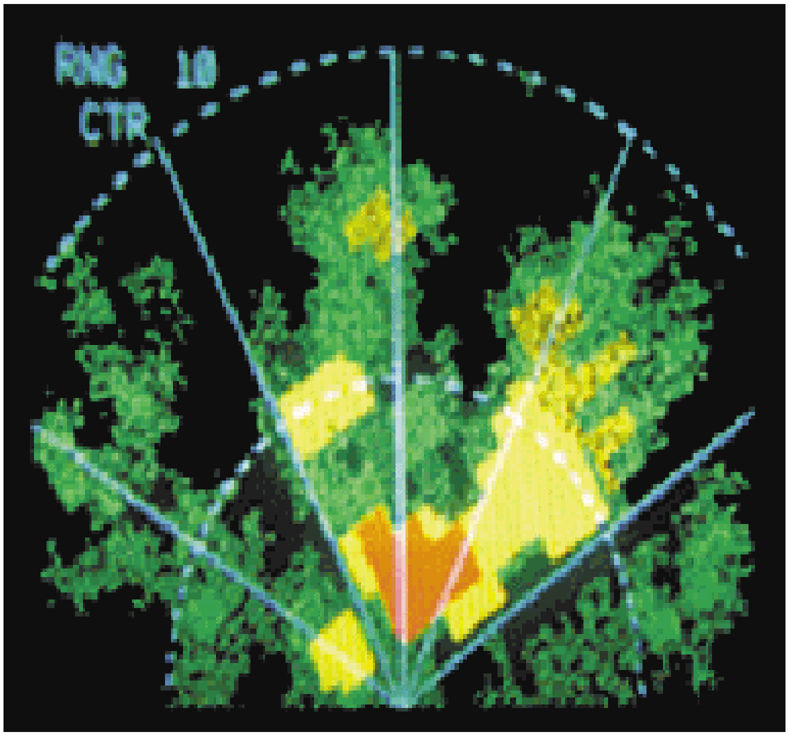


Figure 2-3 EGPWS Terrain Display

2.5.2.3 TAWS TSO-C151

FAA Technical Standard Order TSO-C151 (TSO-C151, 1998) provides minimum operational performance standards that allow certification of the Terrain Awareness and Warning System (TAWS). Note: TAWS is FAA's generic name for future terrain safety systems (e.g., EGPWS, etc.).

A summary of key TAWS TSO requirements is as follows:

1) TAWS should have a probability of an unannunciated loss of the terrain warning functions as a result of equipment failure of less than 10^{-5}. Note: This is consistent with the above noted SVS safety system applications integrity level of 10^{-5}.
2) Navigation to the performance levels of Advisory Circular (AC) 20-130, TSO C-115 or C-129 are considered acceptable for TAWS. TAWS must account for vertical navigation errors of minus 200 ft during enroute operations and minus 100 ft during terminal area and approach operations.
3) TAWS terrain database requirements are as follows:

a) Within 15 nmi of all airports with runways of 3500 ft or greater, terrain grid spacing shall be 15 arc seconds, i.e., 0.25 nmi grid spacing, with 100 ft resolution of elevation data.

b) Within 50 nmi of airports, terrain grid spacing shall be 30 arc seconds, i.e., 0.5 nmi grid spacing, with 100 ft resolution of elevation data.

c) Oceanic and remote areas, terrain may be provided with 5 degree, i.e., 300 nmi grid spacing at 100 ft resolution.

   Note: It is not clear whether the intended meaning is 100 ft resolution or 100 ft accuracy. TSO C-151 refers to resolution, although accuracy may have been intended.

d) TAWS manufacturers shall use RTCA DO-200, "Preparation, Verification and Distribution of User-Selectable Navigation Database" as guidance in the development methodology to validate and verify the terrain and airport database used in TAWS. Note: RTCA DO-200A "Standards for Processing Aeronautical Data" (RTCA DO-200A / EUROCAE ED-76, May 1998) provide new guidance for use of aeronautical databases. The industry is has on-going activities to create improved standards in the preparation and processing of databases for SVS application. This will be further discussed in Section 3 concerning the use of SVS terrain / obstacle databases.

2.5.2.4 GCAS

EUROCAE Working Group 44 is developing minimum operational performance specifications for Ground Collision Avoidance Systems (GCAS) (ED-83, April 1997). Similar to EGPWS / TAWS, GCAS provides a real time comparison between the predicted aircraft flight path and a terrain model. The significant difference between GCAS and EGPWS / TAWS is that GCAS specifies standard recovery maneuvers (i.e., evasive maneuvers) to prevent CFIT. Two classes of GCAS are specified:

1) Class 1 GCAS with a standard vertical recovery maneuver (SVRM),

2) Class 2 GCAS with standard vertical and horizontal recovery maneuvers (SVRM / SHRM).

A class 2 GCAS provides additional protection for operations into terrain difficult airports, where often the intent is not to avoid terrain by climbing over the terrain, but instead to use an appropriate horizontal turning maneuver to fly down a valley along the terrain as one approaches the airport. A class 2 GCAS is expected to give fewer false alarms in this type of environment.

For a class 1 GCAS, terrain cautions and warnings are issued 20 seconds and 5 seconds, prior to the aircraft reaching the vertical reference point, when a standard vertical recovery maneuver is required to clear terrain. For a class 2 GCAS, for a horizontal recovery maneuver, caution and warnings are issued 25 seconds and 10 seconds prior to reaching the horizontal reference point. For a class 2 GCAS, if a horizontal maneuver is not available, the vertical maneuver is actuated for terrain avoidance.

While both GCAS and EGPWS / TAWS have the goals of terrain avoidance, the two systems use different approaches to accomplish the same goal. GCAS includes the escape / terrain avoidance maneuver as part of its alerting algorithm and has fixed alert times. EGPWS / TAWS does not include an escape / terrain avoidance maneuver in its alerting algorithm and provides the maximum amount of warning time to the flight crew to allow the flight crew to take evasive action.

GCAS terrain database requirements specified in ED-83 are summarized in Table 2-1.

	Enroute	Terminal Area
Terrain grid resolution	300 arc sec (~9 km, 5 nmi)	30 arc sec (1 km)
Horizontal accuracy	1000 m	200 m
Vertical accuracy	100 m	50 m
Confidence in accuracy	90 %	90 %
Resolution in height	10 m	1 m

Table 2-1 GCAS Terrain Database Requirements

2.5.2.5 Future SVS Safety System Applications

The previous sections described several terrain avoidance safety systems (GPWS, TAWS / EGPWS, and GCAS) that are playing a role in the current airspace system. GPWS is being replaced with TAWS / EGPWS. GCAS is an alternate candidate to TAWS / EGPWS. The purpose of this section is to identify potential SVS safety system applications that can provide benefits in the future.

The following SVS safety system applications have been identified as potential candidates for future SVS safety system development:

1) Next generation TAWS / EGPWS, referred to as “TAWS Plus”.
2) Take-off engine out procedures / situational awareness for safety
3) Emergency landing in rough / smooth terrain

<u>“TAWS Plus”</u>

“TAWS Plus”, like its TAWS / EGPWS counterpart is similar to TCAS in operational philosophy, where the crew does not actively rely on the TAWS Plus system during normal operations. TAWS Plus, like TCAS is a last resort, safety system, i.e., the flight crew only does “something”, e.g., takes evasive action, when “something” else has gone wrong. This system is also certified as a non-critical, i.e., “non-essential” system, with an integrity level of ~10^{-5} (integrity referring to the probability of unannunciated loss-of-function).

Similar to TCAS, which uses a display for traffic situational awareness, TWAS Plus uses a display for terrain situational awareness. Since TAWS Plus is a non-critical system with ~10^{-5} integrity level, the flight crew must not use the TAWS Plus display for strategic or tactical flight, since the underlying system (e.g., the terrain database) is of insufficient integrity to allow such operations. This is a significant issue, which is further exacerbated when the terrain display is further improved to provide a realistic, high quality appearance of the terrain. Human factors studies indicate that humans tend to assume greater accuracy of the displayed information when this information is depicted in high quality, real formats, even if the underlying data is less than accurate. A low-integrity, situational awareness display of terrain should not be used for strategic planning and tactical guidance, otherwise the system must be upgraded to “essential” or "critical", with associated increases in integrity requirements (probability of unannounced loss-of-function) of $\sim 10^{-7}$ or $\sim 10^{-9}$, respectively.

Potential improvements to "TAWS Plus" are:

1) Upgrade of the terrain display

   The current TAWS / EGPWS uses a 2-dimensional (2-D) display that is low resolution, using the existing weather radar display. An upgraded "2-D Plus" display may be considered that provides higher resolution graphics with additional symbology. The display may also be upgraded to a 3-D terrain graphics display, with perspective or non-perspective views. Again, with these improved displays arises the issue of trusting the display more than is warranted by the underlying system integrity.

2) Using an improved terrain / obstacle database

   The database can be improved to provide greater grid resolution and data accuracy. The current TSO for TAWS requires only a 0.25 nmi terrain grid spacing within 15 nmi of airports, 0.5 nmi grid spacings within 50 nmi of airports, and 300 nmi grid spacings for enroute operations. Databases with considerably greater grid resolution are becoming available and should offer improvements.

   Note: An improved database does not necessarily assure improved database integrity. While the resolution and accuracy may be improved, the probability of undetected misleading information may be relatively high depending on the available database integrity. SVS databases and associated system issues are further discussed in Section 3.

3) Better alerting algorithms

   With improved databases, improved aircraft navigation capabilities based on Required Navigation Performance (RNP), and improved aircraft trajectory prediction using aircraft intent information, further improvements in terrain avoidance alerting algorithms may be possible. TAWS / EGPWS is expected to provide a significant improvement in alerting performance (high success rate in detecting terrain conflicts, low false / nuisance alarms) versus GPWS. As operational experience is gained with TAWS / EGPWS, these algorithms can be further improved for TAWS Plus.

4) Improved evasive maneuvers / guidance

   Addition of evasive maneuvers or using improved evasive maneuvers and guidance can be utilized to further improve TAWS Plus terrain avoidance performance. When used only as a safety system, TAWS Plus can remain a non-critical, $\sim 10^{-5}$ integrity system. However, if TAWS Plus using evasive maneuvers / guidance is used to allow closer flight to terrain from a strategic and tactical perspective, the criticality of the system increases rapidly.

5) Supplemental Data

   Supplementing the TAWS Plus terrain database with data derived from terrain mapping sensors / radars during flight operations. The benefits of using inputs from these enhanced vision sensors need to be investigated.

<u>Take-off Engine Out Procedures / Situational Awareness for Safety</u>

Another potential safety benefit of SVS is to display terrain and obstacle data on cockpit displays during takeoff operations. In the event of an engine failure during takeoff, this additional situational awareness information may be beneficial to the flight crew in providing additional protection against terrain / obstacle hazards. However, as a safety system, this capability does not mitigate the need for rigorous takeoff procedures. Only when terrain / obstacle data is displayed to provide tactical guidance can takeoff procedures be lessened, but at the expense of raising the criticality of the SVS application. The merits of this safety system application require further study.

Emergency Landing in Rough / Smooth Terrain

By supplementing terrain elevation data with additional data indicating the type of terrain (rough or smooth), this SVS safety system application can assist the pilot in selecting the most appropriate site for executing an emergency landing. This is a last resort type application, typical of safety systems, and offers the greatest benefit to general aviation pilots.

2.5.3 SVS Strategic Applications

The previous section identified a number of SVS safety system applications that potentially provide terrain hazard warnings. This section examines potential applications of SVS that may provide benefits to the flight crew in planning and conducting their flight from a strategic perspective. The reference to strategic infers that the flight crew has the appropriate information and situational awareness that allows the flight crew sufficient time to anticipate future events, i.e., the flight crew uses these systems for planning. Strategic SVS applications are differentiated from SVS tactical applications, which focus on very near term events related to guidance along the aircraft flight (SVS tactical applications are discussed in Section 2.5.4).

The SVS applications considered in this section pertain to terrain strategic planning system functions using terrain / obstacle databases. These systems applications are categorized as “essential” and are expected to have integrity requirements of $\sim 10^{-7}$ (i.e., a probability of unannunciated loss-of-function of $\sim 10^{-7}$).

Note: There are currently no SVS strategic applications in operational use in the aircraft fleet. All current fielded systems are associate with providing terrain hazard warnings, which were discussed in Section 2.5.2.

2.5.3.1 Future SVS Strategic Applications

The following three categories of SVS strategic applications been identified as potential candidates that may provide safety and operational benefits:

1) Terrain strategic planning / re-planning system.
2) Flight progress monitor.
3) Surface operations (situational awareness of airport layout, taxi routes).

Terrain Strategic Planning Systems

Terrain strategic planning SVS applications are those that support the flight crew in the development of “terrain safe” flight plans. The current airspace system already uses terrain safe airways and procedures in IFR enroute operations, and uses SIDS and STARS in the terminal area. However, the future airspace system must support more flexible air routes to accommodate future increases in air traffic, i.e., make better utilization of airspace. In addition, airspace operators can gain greater operational efficiency by using more flexible routes, e.g., shorter air routes, favorable wind routes, etc. SVS strategic planning tools will be required to support this increased level of flexible routing (i.e., free flight), while maintaining and increasing the level of safety of current operations. SVS strategic planning tools include “weather planning”, “traffic planning”, and “terrain planning” tools that support the flight crew in planning and executing their intended flight plan / path. Occurrence of a flight path hazard due to adverse weather, proximate traffic or terrain will require a change in flight plan, thus the flight crew can derive benefits from the terrain strategic planning system.

The terrain strategic planning systems discussed in this section support the development of “terrain safe” flight plans. These SVS applications provide strategic flight planning capability, both for pre-flight and in-flight planning.

Pre-flight planning

The terrain strategic planning tool supports pre-flight planning:

1) Preview flight plan with terrain depicted.

2) Contingency planning.

For pre-flight planning, the flight crew develops their flight plan with the support of the SVS terrain strategic planning tool. This SVS application provides accurate and relatively high integrity ($\sim 10^{-7}$) terrain information using the geo-referenced terrain / obstacle databases and performs calculations comparing the flight plan provided by the pilot to the terrain / obstacle database to ensure that adequate terrain separation standards are met. The terrain-planning tool notifies the pilot of potential terrain conflicts in the selected route, allowing the pilot to make necessary adjustments to the flight plan.

The terrain strategic planning tool allows the flight crew to preview their flight plan along with terrain information. For “terrain difficult” flight plans, this tool provides the flight crew with situational / cognitive awareness of difficult terrain. This added cognitive awareness is especially beneficial for departure from a “terrain difficult” airport or at the destination airport that is “terrain difficult”. In fact this tool can be used for training / simulation of departure / approaches from / into terrain difficult airports prior to conducting the actual flight. The planning tool also supports contingency planning. The added situational awareness provided by the terrain strategic planning tool provides benefits of improved safety.

In-flight planning

The terrain strategic planning tool can also be used during flight. The tool allows a number of capabilities:

1) Enroute planning / replanning of later segments of the flight plan.

2) Replan a route to an alternate airport due to weather at the destination.

3) Preview the approach procedure with terrain depicted. This is especially helpful for approaches into terrain difficult airports.

4) Contingency planning

5) After missed approach

6) Replan back for second attempt

7) Replan diversion to alternate airport

Many of the functions of the terrain strategic planning SVS application relate to the planning / replanning of routes that ensure that the new route is “terrain safe”. In addition, this type of SVS application also provides situational / cognitive awareness of difficult terrain. Depending on the phase of flight, the pilot may actually choose to preview a portion of the flight that is particularly difficult due to terrain. For example, while still at the gate, the pilot could preview the takeoff / departure from the airport, or while enroute, the pilot can preview the approach / landing to the destination airport.

Depending on the intended utilization of the SVS terrain strategic planning application, the system supports “terrain-safe” flight planning / replanning, and provides flight plan preview / training / simulation of operations in difficult terrain, both while in preflight on the ground or during flight.

<u>Flight Progress Monitor</u>

SVS terrain strategic planning applications also provide benefits of depicting flight progress relative to terrain via a cockpit strategic display. The flight crew uses this information for flight progress awareness and strategic planning of the remainder of the flight plan. A number of display concepts may be used to portray the strategic flight plan / progress information, ranging from 2-D plan view displays to 3-D displays. Examples of 3-D perspective view displays use exocentric (wing man’s view) or egocentric (own eye view) display views in depicting own aircraft position, the intended flight plan, terrain / obstacles, and possibly cultural features, e.g., rivers, roads and railroads. Cultural features are especially beneficial for low-end general aviation pilots and may also provide benefits for high-end operators during low-level flight (i.e., near terminal areas).

While not the focus of this study, a strategic “flight progress monitor” display would likely also include weather and traffic information and may also include depiction of restricted / special use airspace, thus providing the flight crew with total situational awareness of their flight environment. A full-function SVS strategic display thus requires integration of a variety of information elements that have different characteristics. While terrain and obstacle data are static, other data such as weather and traffic information are highly dynamic in nature. In addition, the aircraft state is constantly changing which also influences the display of information. From Figure 2-1, the SVS application processing function is responsible for integrating these information sources in real time, with the graphics rendering / display manager / image fusion function providing the real-time image to the displays. It is evident that the database architecture and display generation process are integrally related. Section 3 addresses top-level issues related to information database architectures and associated display processing considerations.

<u>Surface Operations</u>

The SVS applications discussed thus far have focused on safety system applications and on terrain strategic planning. For surface operations the focus is not as much on terrain and obstacles, as it is on the airport layout itself. Thus, this type of SVS application requires an accurate airport database.

The surface operations SVS application uses a cockpit display to provide the flight crew with strategic planning information consisting of an accurate layout of the airport and also taxi route information. This application is envisioned to be “essential” with a high system integrity of ~ 10^{-7}.

This SVS application is especially helpful at large airports, with complex airport layouts, and can also provide benefits during night taxi operations and low-visibility weather conditions. When supplemented with traffic information derived via Cockpit Display of

Traffic Information (CDTI) or Traffic Information Services – Broadcast (TIS-B), this also provides runway incursion prevention information to the flight deck. The display can also combine controller-pilot data link communications (CPDLC) messages with the surface map to depict taxi route clearance and controller instructions. In addition, Airport Movement Area Safety System (AMASS) holdbar status information can be datalinked to the aircraft and depicted on the display, thus providing a real-time indication of runway status and providing additional runway incursion prevention safety benefits.

2.5.4 SVS Tactical Applications

The previous section discussed SVS strategic applications that assist the flight crew in planning and conducting the flight in a "terrain safe" manner. This section looks at SVS tactical applications that may provide safety and operational benefits. Unlike strategic applications that are primarily used for planning and are thus not very time critical, tactical SVS applications are concerned with near / immediate term information support needed to fly the aircraft, i.e., tactical SVS applications provide guidance support to the flight crew.

The SVS applications considered in this section pertain to terrain tactical guidance using terrain / obstacle databases. Due to the guidance nature of these applications, these systems applications are categorized as "critical" and are expected to have high integrity requirements of $\sim 10^{-9}$ (i.e., a probability of unannunciated loss-of-function of $\sim 10^{-9}$).

Note: As with SVS strategic applications, there are currently no SVS tactical applications in operational use in the commercial aircraft fleet. Nap-of-the-earth terrain following is of importance the military operations but it is not an appropriate flight mode for commercial aviation.

2.5.4.1 Future SVS Tactical Applications

The most demanding use for synthetic vision is to "fly-the-image" as depicted via a cockpit display, regardless of the outside visual conditions. In essence, the synthetic vision image replaces and even enhances the VFR outside visuals by supplementing the synthetic vision display with other tactical and aircraft state information. "Fly-the-image" is primarily a tactical application related directly to flying the aircraft based on guidance information offered by the synthetic vision "image" of the outside world. Clearly, fly-the image, particularly for low-visibility landing operations, is the highest integrity SVS application that can be envisioned. Such a system requires very accurate terrain and obstacle databases, very accurate navigation, and more importantly, high-integrity databases, navigation, SVS applications processing and SVS display subsystems (at least 10^{-9} probability of loss of function or lower).

SVS applications pertaining to terrain tactical guidance play a major role particularly during phases of flight when the aircraft is in relative close proximity to terrain / obstacles, i.e., during terminal area operations and primarily during approach / landing and takeoff / departure. Commercial aviation will continue to utilize reasonable terrain separation standards during enroute operations, which of course lessens the requirements for terrain grid resolution, accuracy, and integrity.

SVS tactical guidance application may also be an important aspect of low-visibility surface / taxi operations. The following SVS tactical applications have been identified for potential future benefits:

1) Vertical / lateral spatial awareness during approach / landing
2) Pathways-in-the-sky cues (guidance)
3) Fly the SVS Image
4) Approach monitor
5) Approach and landing aid
6) Surface Operations
7) Navigation guidance

Each of these applications are discussed in the following sections.

Vertical / Lateral Spatial Awareness

As indicated in Sections 2.3 and 2.4 on CFIT and loss-of-control accidents, lack of vertical / lateral spatial awareness by the pilot during approach and landing is a major factor in CFIT and loss-of-control accidents. This is especially true for VFR approaches in “black night” (i.e., clear visibility but dark sky / ground conditions) and “whiteout” conditions (i.e., good visibility, but with white sky {clouds} and white ground {snow cover}), with minimal discernible visual cues, and also during non-precision approache (NPA) procedures.

For VFR approaches in black night and whiteout conditions, both lateral and vertical spatial awareness are needed by the flight crew to avoid the potential for errors / loss of situational awareness from becoming factors in CFIT and loss-of-control accidents.

For NPAs, which do benefit from lateral guidance from navigation aids (VOR, DME, NDB, etc.), the primary factor for CFIT accidents is vertical spatial awareness associated with altitude step-downs along the approach path. Many NPA CFIT accidents in fact occur when aircraft are lined up and stabilized on the runway-extended centerline, but failure / loss of vertical spatial awareness results in CFIT short of the runway.

Aircraft conducting precision approaches using ILS, MLS, and in the future GLS (GPS landing system) are very safe, with rare, if any CFIT or loss-of-control accidents. These systems provide the needed lateral and vertical guidance to assure safe operations.

Vertical and lateral spatial awareness can be provided via an SVS display of pertinent terrain / obstacle and airport data along with the intended flight path and current aircraft position. The SVS display could utilize 3-D display formats with appropriate guidance cues for vertical and lateral awareness, or could use a combination of both a 2-D plan view and a 2-D vertical view of the flight path and current position.

The criticality of this SVS application depends on the extent of reliance by the pilot on this application for either tactical guidance or simply as a safety / alerting system. If used for tactical guidance, this SVS application may actually be considered as a pathway-in-the-sky guidance application discussed in next section. As strategic vertical / lateral spatial awareness, this application could be viewed as a SVS strategic application as a flight progress monitor (Section 2.5.3). If used strictly for safety / back-up system, e.g., EGPWS, this vertical / lateral spatial awareness is only intended as a relatively low-integrity, terrain hazard alerting / situational awareness system.

Precision approaches are very safe and provide protection from CFIT and loss-of-control accidents. The question remains to determine what is the appropriate role of SVS relative to the use of precision approaches to help eliminate these types of accidents.

Note: While black night and whiteout are discussed as potential problems during approach / landing, these conditions also provide potential loss of aircraft attitude awareness during enroute operations. Without appropriate visual cues, a pilot may be slow in detecting occurrence of an unusual aircraft attitude perhaps resulting from a slow, undetected roll of the aircraft. SVS display of terrain or the artificial horizon, along with display of aircraft attitude information should provide the necessary information to the flight crew to help prevent this type of loss-of-spatial awareness. It may also be helpful to have an automation system monitor aircraft attitude and provide an attitude caution warning when aircraft attitude exceeds preset limits.

Pathway-in-the-Sky Cues

Pathways-in-the-sky cues provide guidance information to the pilot to fly a prescribed flight path. These guidance cues perform similar functions to localizer and glideslope deviation signals used during approach and landing. Pathways-in-the-sky guidance cues may be used during all phases of flight, from takeoff, terminal area departure, enroute, approach, landing and surface operations. These guidance cues are derived from the aircraft navigation system (which for SVS is assumed to be GPS or augmented GPS / LAAS / WAAS) and the intended flight path. From that perspective, pathway-in-the-sky guidance does not fall into the category of SVS, since SVS implies guidance based on terrain / obstacle databases. However, pathways-in-the-sky guidance cues can be overlayed on SVS data, such as terrain, obstacle, cultural feature and airport database information (and also weather and traffic data for a full-function SVS) for a more realistic depiction of the flight environment.

Since pathways-in-the-sky information is critical in nature (relatively high-integrity from 10^{-7} to 10^{-9}), the integration of this data with other SVS data (terrain, obstacles, etc.) likely requires that all data on the SVS tactical guidance display must also be certified to the flight critical level. This raises an important issue related to the most appropriate use of guidance information, such as pathways-in-the-sky, and the use of SVS display information (i.e., terrain data, etc.) for tactical guidance. There are a number of human factors issues concerning the proper mix of information (format and content) that is most useful to the pilot, and what information is potentially distracting in allowing the pilot to perform his task of flying the aircraft. For example, for takeoff operations, it is not clear whether displaying the terrain / obstacle hazards to the flight deck would be more appropriate than simply using the database with a “guided departure flight path” and provide the flight crew with guidance, i.e., pathway-in-the-sky. This study will not provide an answer to this complex issue, but only identifies it as an area of future research.

Pathways-in-the-sky guidance can take many formats, such as staples / square brackets, goal posts, tunnels, etc. Guidance commands can also be provided as a “follow-me aircraft”. Additional study is required to select the most appropriate guidance formats.

Fly the SVS Image

As indicated earlier, the most demanding use for synthetic vision is to “fly-the-image”. “Fly-the-image” implies a cockpit display that provides a synthesized view of the outside environment based on SVS terrain, obstacle, cultural features, and airport databases, (also weather and traffic data) along with other tactical information, such as “pathway-in-the-sky” guidance, own aircraft position, and aircraft state information. The synthetic vision image thus replaces and even enhances the outside visuals associated with VFR flight. “Fly-the-image” guidance may be used through all flight phases, and requires a very high-level of integrity from the SVS databases, particularly during low-level flight phases, when in close proximity to terrain.

As noted in the “pathway-in-the-sky” application section above, a primary issue concerning SVS displays (such as “fly-the-image” SVS formats), and guidance information (such as “pathway-in-the-sky”), is the proper mix of information (both from an information format and information content perspective) that is optimum for providing the flight crew with the most appropriate guidance information. This raises a number of human factors considerations related to what information is most useful to the pilot / flight crew in conducting the flight, and what information is extraneous and thus potentially distracting to the pilot / flight crew. A “fly-the-image” display without guidance information (such as “pathway-in-the-sky” guidance) may not provide adequate information to the pilot to fly the aircraft safely. Conversely, “pathway-in-the-sky” guidance without any SVS display information is also probably less than optimum. The human factors challenge is to identify the appropriate amount of SVS display information with the appropriate tactical guidance cues. This study will not provide an answer to this question, but only raises this complex issue as an area requiring future research.

Some potential “fly-the-image” applications apply to: 1) takeoff, where the image is rich with terrain / obstacle information, 2) approach and landing, again where the image provides the synthetic vision image of terrain, obstacles, cultural features, and the also airport layout / geometry, and 3) surface operations, where a detailed layout of airport taxiways / runways and associated surface markings / centerline and airport signage information is provided. Essentially, this “fly-the-image” capability allows the flight crew to conduct low-visibility operations by simply flying the image, just as if flying a flight simulator. “Fly-the-image” is somewhat less interesting and likely less helpful during enroute operations, where the terrain information on its own is more benign, blending into the background and thus offers limited guidance. Of course the “fly-the-image” SVS display can be supplemented with strategic and tactical guidance information typically found on the navigation display (ND) and the primary flight display (PFD).

A primary issue of SVS versus guidance is to determine the mix of these two types of information This issue requires human factors study.

Note: As indicated, strict reliance on “fly-the-image” for guidance, particularly for precision approach operations, requires very high system integrity. Due to the expected problem of achieving very high SVS database integrity, it is likely that SVS application will be hard-pressed to achieve ~10^{-9} unannunciated loss-of-function / misleading information requirement for terrain and obstacle data. In that event, it may be necessary to find alternate means, such as independent terrain / obstacle data from an independent source, such as a terrain / obstacle mapping radar to supplement / validate the terrain information derived from the database. The need and feasibility of supplementing SVS terrain / obstacle databases with terrain / obstacle data derived from a terrain / obstacle mapping radar requires further study.

<u>Approach Monitor</u>

In addition to the guidance applications indicated above, SVS tactical applications may potentially be used as an “SVS Approach Monitor”, allowing the availability of SVS visual cues during landing to provide the additional needed information / integrity to allow operations to lower decision height minima. The scenario for the SVS approach monitor application is as follows:

Another guidance signal (e.g., Type I or II ILS or MLS) is being used to provide the primary approach guidance. This guidance signal has the accuracy and integrity to allow a suitably equipped aircraft and crew to fly to the conventional decision height (DH). At the DH and below, in order to continue a conventional the approach, the pilot must have certain visual references: 1) identification of a runway, and 2) the spatial location of the touchdown zone (the exact visual reference requirements are specified in FAR 91.175 (or 121.651) for approaches other than CAT II / III and FAR 91.189 for CAT II / III). Note that the FAA requirements essentially require the pilot to judge whether the aircraft is in a position from which a descent and landing on the intended runway can be made using “normal" maneuvers.

Continuing with the scenario: It is assumed that the primary approach guidance system, such as ILS or MLS, has the accuracy (under fault free performance) to keep the aircraft in proper position to land to a DH that is lower than conventionally approved, but lacks the system integrity to meet this lower DH. The SVS approach monitor application can supplement this system by providing appropriate synthetic “visual” cues replacing the need for actual outside visuals down to the lower DH. The difference between conventional DH and the lower DH represents the net operational benefit provided by the SVS approach monitor application. In this scenario, the SVS approach monitor application increases or “boosts” the available system integrity to meet the integrity requirement down to the lower, SVS aided decision height. Of course, once at the lower DH that is beyond the capability of the combined system (primary approach guidance and SVS approach monitor), the flight crew must be able to visually see the runway or else initiate a missed approach procedure.

The operational cost benefits and technical feasibility of the SVS approach monitor application requires further study. Table 2-2 is offered as an overview of visibility limits (runway visual range, RVR, and decision height, DH) for precision approach and landings. Two additional rows are provided at the bottom of the table indicating the limits are yet to be determined for SVS with and without a head-up guidance system (HGS) to determine the potential operational benefit.

Note: For the above scenario the primary approach guidance system was assumed to be either based on ILS or MLS, while the SVS approach monitor uses augmented GPS, i.e., LAAS or WAAS as its navigation source. This independence of navigation systems facilitates the “integrity boost” provided by the SVS approach monitor. If the primary approach guidance system instead uses the GPS navigation source (i.e., GLS approach guidance), then the independence between the primary approach guidance system and the SVS approach monitor is compromised and the potential for operational benefits are also compromised unless another means for boosting integrity is found.

Note: While the focus of discussion has been on system integrity, system availability and continuity of function must also be considered, but are not discussed here.

Approach and Landing Aid

In addition to the SVS approach monitor application, SVS may potentially provide operational cost benefits as an approach and landing aid. As an approach landing aid, this SVS application could provide economic benefits by providing an image that could be used in lieu of certain convention ground infrastructure requirements like runway lighting and markings.

Type I	Type II	Type III

					CAT IIIa		CAT IIIb	CAT IIIc
	Caveats	W / O FTDZ	TDZ & CLL		Fail Passive	Fail Op.	Fail Op. AL or Fail Ps. AL & Fail Ps. HGS	Fail op. AL & Rollout
No HGS (Conventional)	RVR	≥ 2400	≥ 1800	≥ 1200	≥ 700	≥ 700	≥ 300	≥ 0
	DH	≥ 200	≥ 200	≥ 100	≥ 50	≥ 0	≥ 0	≥ 0
HGS	RVR	≥ 1800 (1600*)	≥ 1600* (1200*)	≥ 700	≥ 700	≥ 700	≥ 300	≥ 0
	DH	≥ 200 (150*)	≥ 150* (100*)	≥ 50	≥ 50	≥ 0	≥ 0*	≥ 0
EVS (wo / HUD)	RVR	≥ 1200*	≥ 1200*	≥ 700*	≥ 700	≥ 700	≥ 300	≥ 0
	DH	≥ 100*	≥ 100*	≥ 50*	≥ 50	≥ 0	≥ 0	≥ 0
EVS (w / HGS)	RVR	≥ 700*	≥ 700*	≥ 700	≥ 700	≥ 700	≥ 300	≥ 0
	DH	≥ 50*	≥ 50*	≥ 50	≥ 50	≥ 0	≥ 0	≥ 0
SVS (wo / HUD)	RVR	?	?	?	?	?	?	?
	DH	?	?	?	?	?	?	?
SVS (w / HUD)	RVR	?	?	?	?	?	?	?
	DH	?	?	?	?	?	?	?

* May not yet be certified

Table 2-2 Precision Approach & Landing: RVR and DH Requirements Overview

Traditional approach operations use navigation and guidance aids (e.g., ILS), barometric altimeters, and sometimes radar altimeters which provide a safe approach, landing, and roll-out operation when coupled with an airport infrastructure that includes lighting systems, markings, and signs. The airport infrastructure is required to provide the flight crew with the visual information necessary to complete the approach and landing. For example, to help identify the touchdown environment, approach lights, threshold lights, runway touchdown zone lights, runway markings, etc. are used. To assist the flight crew to guide the aircraft down the runway, runway lights and markings (centerline and edge), as well as signs (providing runway remaining) are used.

SVS may be able to displace some of the airport infrastructure requirements (including lights, markings, and signs) by providing equivalent information. But as noted earlier, if both the precision approach system and the SVS approach and landing aid application utilize GPS than some of the independence of function provided by airport lighting is lost, and the GPS position information must have even greater integrity than that used by the precision approach system itself.

Thus the potential economic / operational benefit for an aircraft equipped with SVS approach and landing aid capability, is that it may be possible to perform CAT I approach operations on a runway that has only conventional non-precision approach lighting and markings. Similarly, it may be possible to perform a CAT II or CAT III operation on some CAT I lighted and marked runways. These would obviously have to be approved on a case-by-case basis where equivalent situational awareness information would be provided by the SVS system.

The operational cost benefits and technical feasibility of the SVS approach and landing aid application requires further study. Table 2-3 provides an overview of taxi visual aid requirements in terms of taxiway lighting / reflectors, etc. It is to be determined how SVS can be used in the flight deck as an approach and landing aid to possibly reduce the need for airport lighting / signing / marking infrastructure.

	Visual Aid Requirements					**Surface Movement Surveillance Systems**
	Taxiway Lighting & Reflectors	**Lights at Access to Active Runways**	**Clearance Bars / Markings**	**Taxi Guidance Signing and Markings**	**ILS Critical Area Lights & Markings**	
RVR ≥ 600	Movement Area: 1. CLL with raised edge reflectors on curves / turns, or 2. Taxiway edge lights Non-Movement Area: No Requirements	• Taxi-holding position lights	• Painted markings to denote hold points	Intersection guidance 1. Signs or 2. Painted Markings	1. Taxiway CLL alternate green and amber or 2. Where CLL not installed, install a sign	• Not Required
RVR < 600	Movement Area: CLL supplemented with edge lights on curves / turns Non-Movement Area: CLL or taxiing assistance	• Taxi-holding position lights • Stop Bars	• Painted markings to denote hold points • Clearance bars	Intersection guidance • 1. Signs or 2. Painted Markings • Geographic position marking to ID hold points	1. Taxiway CLL alternate green and amber or 2. Where CLL not installed, install a sign	• System to establish position of the aircraft / vehicles

CLL = center line lighting Reference: AC120-57 SMGCS

Table 2-3 Summary of Taxi Visual Aid Requirements

Surface Operations

Surface operations were discussed as one of the SVS strategic applications (Section 2.5.2). For strategic use, SVS provides taxi route planning and situational awareness for surface operations. SVS surface operations can also be used for tactical guidance of the aircraft on the airport surface during low-visibility conditions. In this situation the pilot steers the aircraft on the taxiways based on the SVS guidance. Again an accurate airport data base is required along with DGPS navigation. SVS tactical surface operations requires high system integrity, i.e., will be flight critical (~10^{-9} probability of undetected system failure). A display of other aircraft and other surface traffic is also required to prevent collisions. Surface operational information is also required guide the pilot on his approved taxi routing and to prevent runway incursions.

Navigation Guidance

With accurate DGPS navigation, and availability of accurate terrain / obstacle database information, the thought occurs that SVS could in fact be used for navigation guidance or at least to supplement a primary navigation system with SVS navigation guidance. To consider these applications it is helpful to examine requirements for a conventional precision approach guidance system.

As an example, for precision approaches below 100 ft AGL (below Cat II), there is an FAA Advisory Circular (AC 120-28C) requirement that the loss of guidance below 100 ft AGL will be extremely improbable (i.e., 10^{-9} per approach). If the primary guidance system only supports precision approaches to a 200 ft decision height, DH, from a navigation accuracy perspective (e.g., Cat I ILS), then SVS navigation could be considered as a supplement to the ILS Cat I primary guidance system to achieve Cat II capability. While this is simply stated, what is being said in essence is that from Cat I DH down to Cat II DH, the SVS provides the primary means of navigation due to greater navigation accuracy. This being the case, then why even consider using a Cat I ILS for the initial portion of the approach / landing down to the Cat I DH, when SVS is capable of greater accuracy (lower Cat II) precision approach capability. Thus, when only one navigation system is capable of full system navigation accuracy, it should serve as the primary precision approach guidance system.

The next issue to explore is if an SVS navigation system is capable of achieving highly-accurate, high-integrity primary guidance for precision approaches. The requirements of such as system are that the GPS position information and associated SVS terrain / obstacle / and airport databases are also highly accurate and also satisfy the integrity requirement that is on the order of 10^{-9}. This is extremely difficult and costly to achieve based on the current state-the-art of SVS terrain / obstacle / airport databases. In addition, a LAAS (augmented GPS) precision approach system is considerably more simple, providing accurate and high-integrity precision approach waypoints in place of SVS terrain / obstacle / airport databases.

For precision approaches, the basic issue is whether SVS provides primary precision navigation guidance capability that is of equal or greater accuracy, integrity and cost compared to more conventional precision approach navigation guidance systems such as ILS, MLS, or GLS. Due to the significant issues associate with the SVS databases, the likely answer is that SVS navigation is not a feasible replacement to conventional precision approach guidance systems.

For navigation using Required Navigation Performance (RNP) in enroute operations, navigation requirements are more modest compared to those associated with precision approaches. Conventional navigation aids of DME, VOR, and NDB, and newer GPS / WAAS / LAAS are capable of providing the necessary RNP. SVS navigation for RNP purposes essentially uses the GPS portion of SVS that maintains the RNP. The SVS databases do not play a role in RNP since RNP is related to navigation performance relative to the intended flight path, which is not determined by the SVS databases. Thus, there is really no difference in RNP navigation between GPS and SVS, since both use GPS to achieve RNP.

SVS for navigation purposes is likely not technically and economically feasible compared to conventional navigation systems for precision approaches or enroute RNP.

2.5.5 Safety / Operational Benefits of SVS – Overview

Section 2.4 provided a discussion of a number of potential uses of synthetic vision system (SVS) applications that provide benefits of improved safety and / or operational efficiency. These applications are summarized in Table 2-4 and the expected benefit(s) of each application are identified. It should be noted that each of these applications potentially provide benefits, but must be further developed to determine their ultimate feasibility for use in the flight deck.

From Table 2-4, the SVS safety system applications only provide safety benefits in terms of terrain hazard warnings and situational awareness, but cannot provide operational benefits. They accomplish their intended function of being a system of last resort in the event of failures of other systems. The relatively low-integrity of these applications prevent their use for anything other than hazard alerting.

SVS strategic applications provide both safety and operational benefits. These benefits are derived somewhat indirectly, i.e., not directly attributable to a specific type of flight operation: 1) safety benefits are obtained by ensuring that the intended flight path / plan is in fact “terrain safe” (i.e., devoid of any threatening terrain), and 2) operational benefits are obtained by supporting the concept of flexible routing or free flight, facilitating relatively easy flight path changes as needed throughout the flight. Strategic applications require moderate system integrity.

The applications best suited for providing operational benefits / efficiency of operations are the tactical SVS applications. These applications provide tactical guidance to lower minima and at higher levels of integrity, thus allowing operations to be extended beyond conventional limits, e.g., lower RVR and DH minima during approach and landing, or flight into terrain difficult areas during low-visibility weather. These applications typically require the highest level of system integrity, since they are used in the direct guidance of the aircraft along its intended flight path.

SVS Application Category	Candidate SVS Applications	Potential Benefit
Safety System Applications (non-essential) (~10^{-5} integrity level)	Existing GPWS / EGPWS / TAWS / GCAS	Safety (terrain hazard alerting)
	TAWS Plus (next generation TAWS)	Safety (terrain hazard alerting)
	Take-off engine out procedure / situational awareness	Safety (terrain hazard alerting)
	Emergency landing in rough / smooth terrain	Safety (last resort guidance)
Strategic Applications (essential) (~10^{-7} integrity level)	Terrain strategic planning / replanning system	Safety and operational (flexible routes)
	Flight progress monitor	Safety and operational (flexible routes)
	Surface operations (situational awareness of airport layout / taxi routes)	Safety and operational (runway incursion protection, efficient taxiing)
Tactical Applications (critical) (~10^{-9} integrity level)	Vertical and spatial awareness during approach and landing (criticality / integrity dependent on whether application is used for safety / situational awareness or tactical guidance)	Safety (CFIT, loss-of-control prevention) or Safety (tactical guidance)
	Pathway-in-sky cues	Safety and operational (terrain safe routes, enhanced operations in terrain difficult areas in low-visibility conditions)
	Fly-the-image	Safety and operational (terrain safe routes, enhanced operations in terrain difficult areas in low-visibility conditions)
	Approach monitor (criticality / integrity in range of essential to critical, i.e., (~10^{-7} to 10^{-9} integrity)	Operational (lower landing minimums)
	Approach and landing aid, and Surface Operations (criticality / integrity in range of essential to critical, i.e., (~10^{-7} to 10^{-9} integrity)	Operational (reduced airport infrastructure)
	Navigation	No apparent advantage over conventional nav. guidance systems

Table 2-4 Summary of Potential SVS Applications and Anticipated Benefits

2.6 Top-Level Synthetic Vision System Requirements

Section 2.5 described candidate Synthetic Vision System (SVS) applications that potentially provide benefits of increased safety and / or improved operational efficiency. In this section, top-level system requirements are identified for each of the major SVS sub-systems needed to provide the necessary functionality these applications. From Figure 2-1 the major SVS sub-systems are: 1) aircraft navigation and position sensors, 2) geo-referenced databases, 3) SVS application processing, and 4) display graphics generation (graphics rendering, display manager, and image fusion), and 5) flight deck displays. (Note that aircraft navigation and position sensors, while shown separately in Figure 2-1, are combined for purposes of the discussion).

Before top-level requirements can be discussed for each of these sub-systems, it is useful to review Federal Aviation Regulations (FARs) concerning flight minimums and separation standards pertinent to synthetic vision (Section 2.6.1), review intended operational flight phases (Section 2.6.2), and provide an example of a fault tree diagram that illustrates how overall system integrity may be achieved (Section 2.6.3). Top-level system requirements are then discussed for each of the SVS sub-systems (Sections 2.6.4 to 2.6.8).

2.6.1 Summary of Federal Aviation Regulations Pertinent to SVS

The following are excerpts of Federal Aviation Regulations (FARs) that concern flight minimums and standards pertinent to synthetic vision. These regulations set requirements for procedures and capabilities that ultimately determine terrain database accuracy. FAR regulations are provided in tabular form in Table 2-5.

Reference	Detailed Description of Regulation
FAR 91.155	VFR weather minimums. There are six classes of airspace (A, B, C, D, E and G). Classes B, C, and D have 3 statute mile visibility requirement and Classes G and E have 5 statute mile requirements for VFR. There are different day and night requirements, but in summary, all aircraft must be 500 feet below the clouds or 1000 feet above the clouds and be at least 2000 feet horizontally clear from all clouds.
FAR 91.177	Minimum Altitudes for IFR Operations. All IFR rated aircraft will fly at least a minimum of 2,000 feet above the highest terrain point within 4 horizontal nautical miles of a course over mountainous terrain, and a minimum of 1,000 feet above such points over non-mountainous terrain.

Table 2-5 Excerpts from Federal Aviation Regulations Pertinent to SVS

2.6.2 SVS Operational Flight Phases

The following operational phases and flight phases, as defined by the AGATE Operational Requirements document (Operational Requirements for AGATE Project, Version 1.1, June 1996), are considered for development of synthetic vision applications:

1) Pilot training
2) Preflight planning
3) Flight planning
4) Taxi to runway
5) Takeoff
6) Departure
7) Enroute
8) In-Flight planning / replanning
9) Terminal operations
10) Approach
11) Aborted / missed approach
12) Diversion to alternate
13) Landing
14) Taxi to ramp

From this relatively long list of operational / flight phases, two distinct, more general groupings of SVS flight phases were developed. The first grouping is by aircraft flight phases that are linked temporally, i.e., operational phases that follow sequentially in time. For example, takeoff is grouped with departure, while approach is grouped with landing. The takeoff phase transitions directly into the departure phase as the aircraft leaves the terminal area. As the aircraft enters the terminal area, approach operations transitions to landing. Table 2-6 lists this temporal grouping, which is used later in the description of SVS operational scenarios (Section 2.7).

Operation	***Flight Phase from AGATE List***
Planning / replanning / training	1, 2, 3, 8
Airport (taxi in / out, surface operations)	4, 14
Takeoff / departure	5, 6
Landing / approach	13, 10
Enroute, diversion to alternate	7, 12
Missed approach (Go-Around)	11

Table 2-6 Temporal Grouping of Operational / Flight Phases

The second grouping of flight phases was developed to better suit the development of SVS terrain and obstacle database requirements. For this method of grouping, flight phases were grouped based on the spatial location of operations relative to the airport. Thus takeoff and landing operations are paired due to their close proximity to the airport itself. Likewise departure and approach are paired due to their spatial proximity to the airport. Table 2-7 lists this spatial grouping, which is used in the development of database requirements.

Operation	***Flight Phase from AGATE List***
Planning / replanning / training	1, 2, 3, 8
Airport (taxi in / out, surface operations)	4, 14
Takeoff / landing / missed approach	5, 11, 13
Departure / approach / terminal operations	6, 9, 10
Enroute / diversion to alternate	7, 12

Table 2-7 Spatial Grouping of Operational / Flight Phases

2.6.3 System Integrity Overview – Fault Tree Diagram

This section briefly examines the issue of SVS integrity and continuity. Integrity is an attribute of the system indicating that it can be relied upon to work correctly. Failure of integrity is the occurrence of an undetected failure where the flight crew does not have an indication that an abnormal condition exists. Thus a high-integrity system has a low probability of undetected / unannunciated system failures, where misleading information may be inadvertently used without knowing that the system has actually failed. As discussed in Section 2.5.1, typical system integrity for SVS applications range from $\sim10^{-5}$ to $\sim10^{-9}$.

Continuity represents the ability of a system to perform its intended function without interruption during intended operation. A failure of continuity is a detected failure, where the crew has an indication that an abnormal condition exists. A high-continuity system thus has a low probability of detected failure. Typical avionics systems exhibit detected failure rates on the order of $\sim10^{-5}$ per flight hour.

Figure 2-4 provides an illustration of how integrity and continuity may be achieved for a generic SVS system. As shown in Figure 2-4, the basic SVS components are the navigation, display, computer and database sub-systems. The navigation sensor, display and computer portions of the system each have associated MTBF (mean time between failure) numbers. The combination of the various MTBF sets the system failure rate. As shown in the diagram, P_2, $P_{3,}$ and P_4 are the probability of sub-system failure for the SVS navigation sensor, display and computer, respectively, which are equal to 1/MTBF.

System monitors and BITE (built-in-test equipment) are used to detect when a failure has in fact occurred. As an example (in Figure 2-4), the monitor / BITE function associated with the navigation sensor is assumed to detect 95% of actual failures (or 5% of failures are undetected). Similarly, display and computer monitor / BITE functions are assumed to detect 99.5% of all failures (with 0.5% of failures going undetected).

The contribution to system integrity (undetected failures) of MTBF is the probabilities of failure times the probability that the monitor / BITE function was unable to detect the failure. The MTBF contribution to continuity is the probability of a failure times the probability that the monitor / BITE function is able to detect the failure.

In addition to MTBF, other contributing factors to system failure are:

1) The probability that the navigation system is unable to stay within the containment boundary (C) when performing properly, (i.e., total system error > C) as represented by $P_{1;}$
2) The probability that the terrain / obstacle database contains errors in the data, as represented by P_5.

These two factors cannot be mitigated by system monitor / BITE functions, and thus add directly into the undetected failure rate of the system.

To achieve system integrity and continuity goals, the system architect may utilize system redundancy and system monitoring / BITE. Continuity is improved by having redundant systems, thus ensuring that at least one system is operational. Integrity may also be improved via redundant systems by allowing system outputs to be compared, thus allowing detection of a failure. Integrity is also improved by providing improved monitoring and BITE.

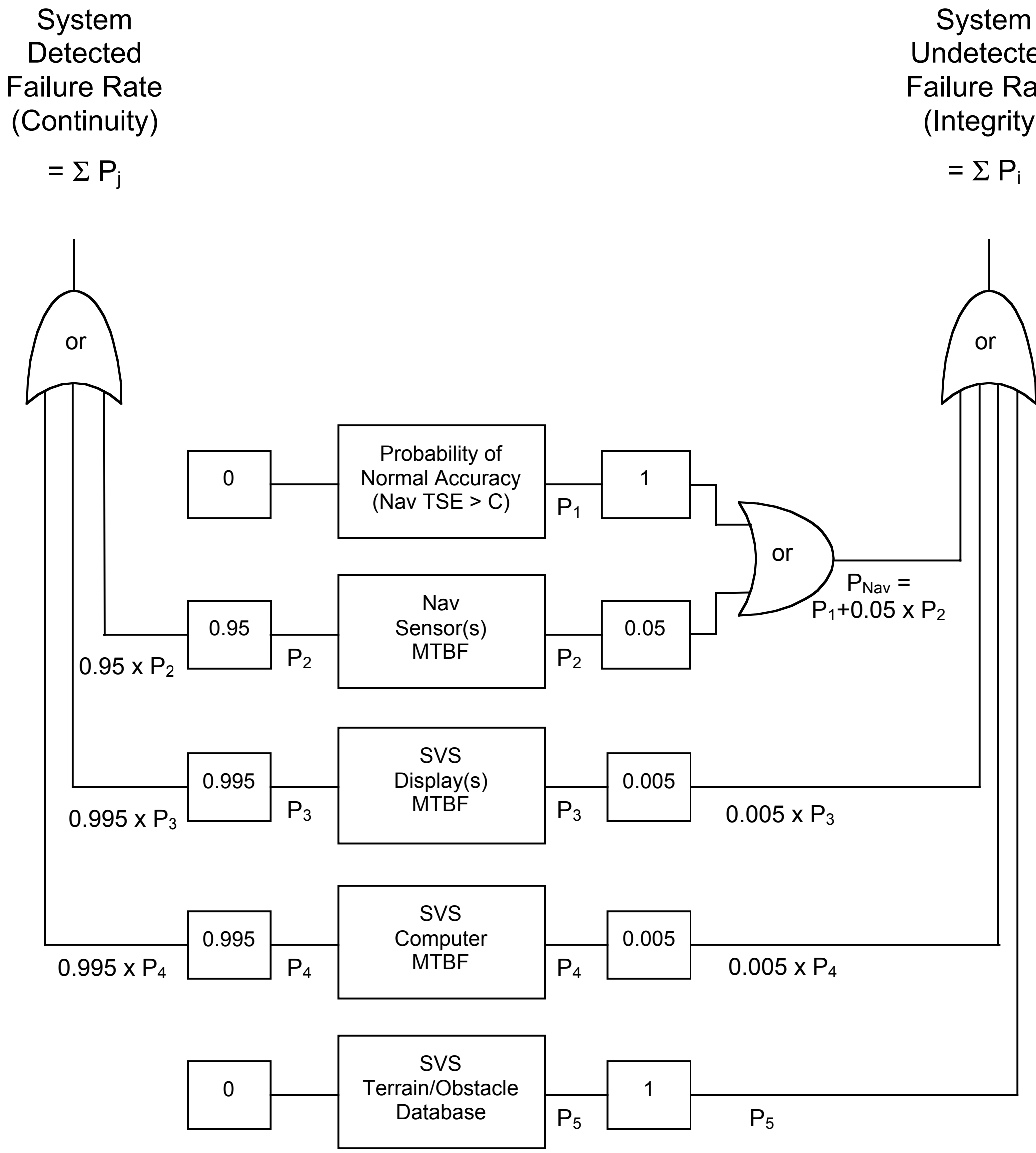


Figure 2-4 SVS Integrity and Continuity Fault Diagram

A significant issue for SVS is the integrity associated with the SVS database. System integrity is directly impacted by the integrity of the source data (as noted by the direct input of P_5 into the OR gate). Thus if the source data has inadequate integrity (i.e., contains some undetected errors), then the SVS also has inadequate integrity. For the high-integrity tactical SVS applications such as “fly-the-image” (i.e., integrity on the order of ~$10^{-9)}$ the SVS terrain / obstacle database must have integrity that is somewhat lower than ~10^{-9}, since the rest of the system will also contribute to the undetected failure rate. Section 3 takes a closer look at the SVS database integrity issue.

2.6.4 Aircraft Navigation, Attitude, and Position Sensor Requirements

The following sections address top-level SVS sub-system requirements. This section addresses navigation, position, and aircraft attitude sensor requirements to support the SVS applications discussed in Section 2.5.

Conventional navigation systems in use today are VOR, DME, NDB, ILS, and MLS. ILS and MLS are used for precision approaches. VOR, DME, and NDB are used for enroute area navigation and also to support non-precision approaches. These systems are also used to determine aircraft position.

GPS is expected to become the future navigation and positioning system for all phases of operation, including precision approaches. Augmentations of GPS with differential correction information from ground or satellite data links allow greater accuracy and integrity. The two types of augmented GPS systems are the Local Area Augmentation System (LAAS), and the Wide Area Augmentation System (WAAS). In addition to these navigation and positioning systems / sensors, the FMS integrates navigation sensor inputs to provide area navigation capabilities for aircraft.

In addition to these sensors, aircraft are assumed to be equipped with conventional aircraft attitude and air data sensors.

In order to provide navigation performance specifications for future airspace system operations and area navigation, RTCA SC-181 developed the concept of Required Navigation Performance (RNP) (RTCA DO-236, January, 1997). The basis for RNP is that aircraft meeting a specific RNP have a 95% probability of maintaining lateral containment within the specified containment boundary. For example, RNP-1 indicates 95% containment to a lateral tunnel of 1 nmi. It is expected that specific RNP capability will be required in order for aircraft to participate in certain airspace operations. In addition, as part of Automatic Dependent Surveillance (ADS, ADS-B) aircraft will transmit their RNP / ANP (actual navigation performance) capability for separation assurance. In order to achieve a specific RNP, an aircraft must have the proper complement of navigation sensors and FMS capability.

Navigation and positioning requirements for the SVS safety system applications (Section 2.5.2) can be met by standard GPS or equivalent navigation sensors for operations down to non-precision approaches. The TAWS TSO C-151 specifies navigation performance as indicated in TSO C-115 and TSO C-129. The more stringent requirement is the GPS 2-D area navigation requirement of position fixing error of 0.124 nmi (~230 m) for enroute and terminal area flight and 0.056 nmi (~100 m) for non-precision approach (95% confidence). The TAWS TSO also indicates an allowable vertical error of –200 ft enroute and –100 ft in the terminal area and on approach.

Strategic SVS applications such as terrain strategic planning and flight monitoring can also be easily met by GPS. For enroute operations, RNP of 1 to 3 nmi should be adequate to provide terrain safe navigation and planning. As one approaches the terminal area of airports that have difficult terrain, RNP of 1 nmi or less will likely be needed.

Note: Much depends on how future terrain separation standards based on use of terrain databases will be developed. From Table 2-5, FAR 91.177 indicates that all IFR rated aircraft must fly at least a minimum of 2,000 feet above the highest terrain point within 4 horizontal nautical miles of a course over mountainous terrain, and a minimum of 1,000 feet above such points over non-mountainous. If these standards will continue to be used for SVS applications, then the RNP stated above should be sufficient, with the rest of the distance being allocated to terrain database accuracy. Since GPS provides RNP << 1 nmi, GPS should support all strategic SVS applications down to non-precision approach.

Tactical SVS applications will require RNP of less than 1 nmi during enroute operations for “fly-the-image” and “pathway-in-the-sky” applications, primarily in order to provide adequate registration of terrain database and pathways displays with the outside visual view of terrain. The remaining tactical SVS applications are related to approach and landing in support of precision approach operational benefits. These applications, along with strategic and tactical SVS surface operations will require DGPS precision navigation capability (~ 1 to 2 m horizontal, ~ 2 to 5 m vertical).

Critical SVS tactical applications may require the need for independent position determination / verification. Available methods include ground-mapping mode of weather radar, use of radar reflectors, and multilateration using ground and / or airborne transponders.

2.6.5 Geo-Referenced Databases Requirements

This section identifies SVS database requirements that are needed to support the SVS applications identified in Section 2.5. The following databases are considered:

- Terrain
- Obstacle
- Cultural features
- Airport
- Navigation

Database requirements are categorized by flight phases using the spatial groupings of Table 2-7. Spatial groupings of flight phases relative to the airport location are preferred since they in essence represent concentric distance rings around the airport. Database resolution and accuracy requirements are greater in the vicinity of the airport and become less stringent for enroute operations. Figure 2-5 shows the location of flight phase areas relative to the airport.

A few items of note from Table 2-8: The terrain resolution for takeoff / landing of 6 arc-seconds represents a grid spacing requirement of ~200 meters. Airport Safety Model Data (ASMD) is currently being provided by National Oceanic and Atmospheric Administration (NOAA) Aeronautical Charting Division for a 12 nmi by 12 nmi square centered around the airport reference point.

The 30 arc-second grid spacing (~0.5 nmi or 0.9 km) for departure / approach is adequate for most areas. However, in terminal areas of “terrain-difficult” airports, 15 arc-second grid spacing (~ 0.25 nmi or 0.5 km) may be needed to avoid the terrain floor filling in the valleys, i.e., raising of the terrain floor due to lack of grid resolution. 15 arc-second ASMD data is available for the terrain difficult airports in the US for a 100 nmi by 100 nmi square centered at the airport.

<u>Terrain Database Requirements</u>

Table 2-8 provides a summary of the terrain database requirements discussed in the following sections for the various phases of flight.

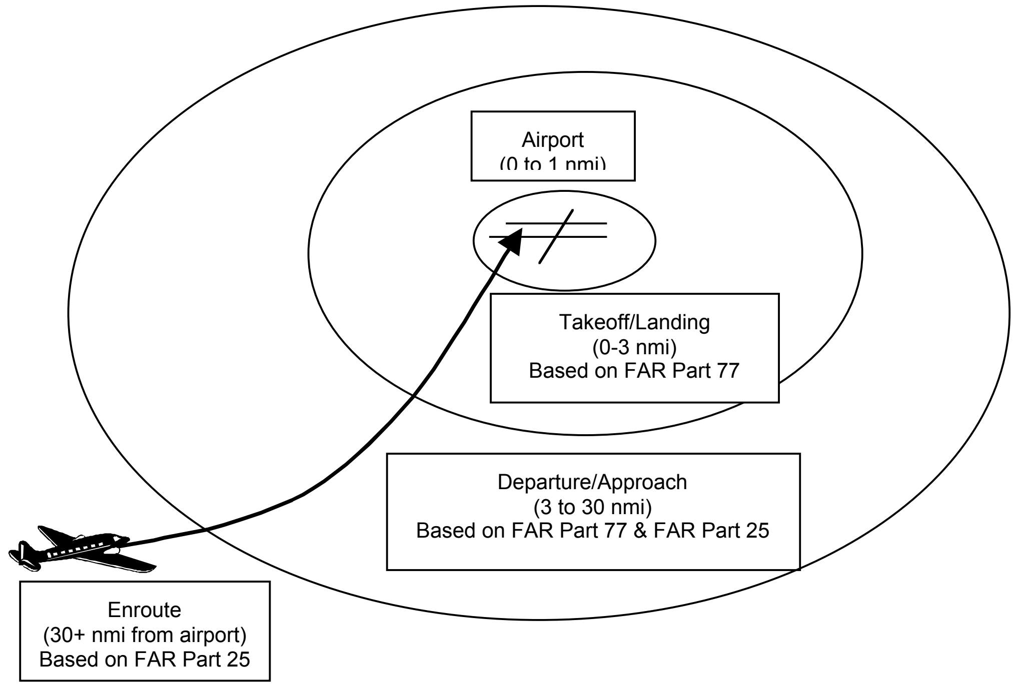


Figure 2-5 Flight Phase Operational Areas

Terrain Data	Airport	Takeoff / Landing	Departure / Approach	Enroute
Resolution	1 meter	6 arc-seconds	30 arc-seconds *	30 or 150 arc-seconds
Horizontal Accuracy	1 meter	30 meter	130 meter	130 or 1000 meter
Vertical Accuracy	1 meter	10 meter	30 meter	100 meter
Confidence	95%	90%	90%	90%

* could increase to 15 arc-second resolution for mountainous airports

Table 2-8 Terrain Database Requirements

Terrain resolution for enroute operations (Table 2-8) requires further explanation. Two ranges for resolution and accuracy are offered as potential requirements: 150 arc-second (~2.5 nmi) or 30 arc-second (~0.5 nmi) grid spacing, with 1,000 meter or 130 meter horizontal accuracy, respectively. The larger grid spacing is relatively coarse and is more inline with currently specified terrain resolution for GCAS. EUROCAE ED-83 (minimum performance specifications for GCAS) calls for 300 arc-second (~5 nmi) grid spacing with 1,000 meter horizontal accuracy for enroute operations.

From a ground collision safety system, this ~5 nmi uncertainty in terrain location impacts alerting time by 30 seconds for aircraft traveling at 600 kts, 60 seconds at 300 kts, and 120 sec at 150 kts. Since enroute operations are planned along “terrain safe” routes, this relatively coarse grid spacing requirement may be suitable for a safety system such as GCAS. Figure 2-6 provides an illustration of a terrain hazard warning scenario.

The aircraft in Figure 2-6 is enroute on level flight, when it eventually encounters threatening terrain. The actual physical terrain is shown in the shaded area. The maximum terrain uncertainty is shown in the dashed line, which accounts for the vertical and horizontal errors in the terrain database. For this example, it is assumed that the warning system must provide an alert that allows an evasive climb maneuver to provide a minimum of 500 ft miss distance to terrain. The evasive maneuver must commence at the reference point in order for the aircraft to clear the terrain. Prior to the reference point, a terrain caution / warning is issued as needed (for example, a caution may be issued 20 seconds prior to reference point, while a warning may be issued 5 seconds before the reference).

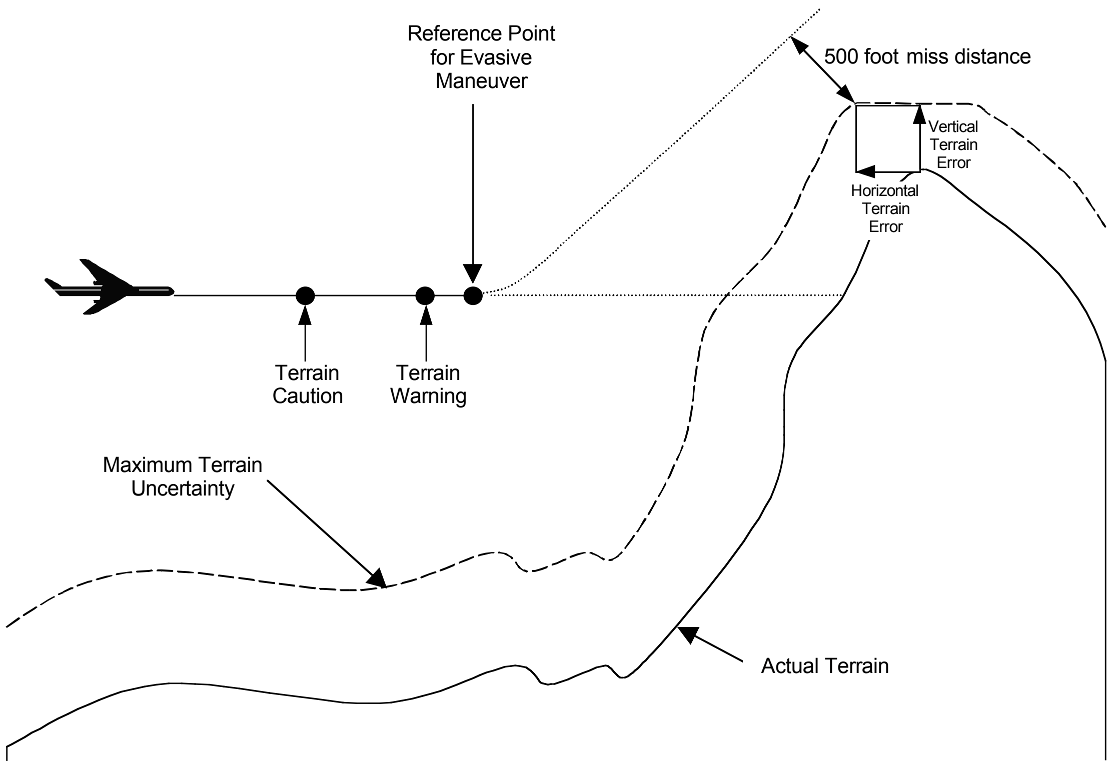


Figure 2-6 Terrain Warning / Clearance Scenario

Using an approach similar to the one use by GCAS, Table 2-9 shows typical reference point distances (i.e., when evasive maneuver is required) as a function of terrain height above flight path for a range of aircraft speeds (150, 300, 600 kts) and climb evasive maneuvers capability (2000 ft per min, 4000 ft, min climb rates). The 300 arc-second (~5 nmi) grid spacing and 1 km horizontal accuracy adds ~5.5 nmi terrain uncertainty. For high-end air transport and business jet aircraft traveling at 600 kts, this additional ~5.5 nmi terrain uncertainty is a relatively smaller percentage of typical reference point distances, while it is significant relative to slower speed aircraft. Since high-speed aircraft require greater separation from terrain (or earlier warning) this relatively coarse terrain grid spacing is not a big factor. Slower aircraft could be allowed to get closer to terrain (i.e., require less warning distance). For these aircraft, this grid spacing may be too coarse, having an effect of requiring unnecessarily large safety buffers.

Another perspective on enroute terrain resolution / grid spacing requirements comes from FAR 91.177. FAR 91.177 requires that all IFR rated aircraft must fly at least a minimum of 2,000 feet above the highest terrain point within 4 horizontal nautical miles of a course over mountainous terrain, and a minimum of 1,000 feet above such points over non-mountainous terrain. This scenario is depicted in Figure 2-7.

Figure 2-7 illustrates an aircraft flying between terrain. Also shown are the 4 nmi terrain clearance buffers that constrain where the aircraft is permitted to operate. The aircraft has associated with it a certain navigation capability, which is indicated as a total system error boundary in the diagram. The current IFR terrain separation standards were developed to allow for errors in terrain maps and also to account for typical aircraft navigation capability supported by current navigation aids. This raises the following issue: Will future terrain separation standards remain the same (as in FAR 91.177) or will availability of accurate terrain databases and aircraft SVS capabilities for strategic and tactical flight guidance allow reduction in these separation standards?

Terrain Height above Aircraft Flight Path	Aircraft at 150 kts, 2000 ft / min Climb Maneuver	Aircraft at 150 kts, 4000 ft / min Climb Maneuver	Aircraft at 300 kts, 2000 ft / min Climb Maneuver	Aircraft at 300 kts, 4000 ft / min Climb Maneuver	Aircraft at 600 kts, 2000 ft / min Climb Maneuver	Aircraft at 600 kts, 4000 ft / min Climb Maneuver
1,000 ft	7,500 ft	3,750 ft	15,000 ft	7,500 ft	30,000 ft	15,000 ft
2,000 ft	15,000 ft	7,500 ft	30,000 ft	15,000 ft	10 nmi	30,000 ft
4,000 ft	30,000 ft	15,000 ft	10 nmi	30,000 ft	20 nmi	10 nmi
6,000 ft	7.5 nmi	22,500 ft	15 nmi	7.5 nmi	30 nmi	15 nmi
8,000 ft	10.0 nmi	30,000 ft	20 nmi	10.0 nmi	40 nmi	20 nmi
10,000 ft	12.5 nmi	6.25 nmi	25 nmi	12.5 nmi	50 nmi	25 nmi

Table 2-9 Typical Reference Point Distances for Terrain Evasive Maneuvers

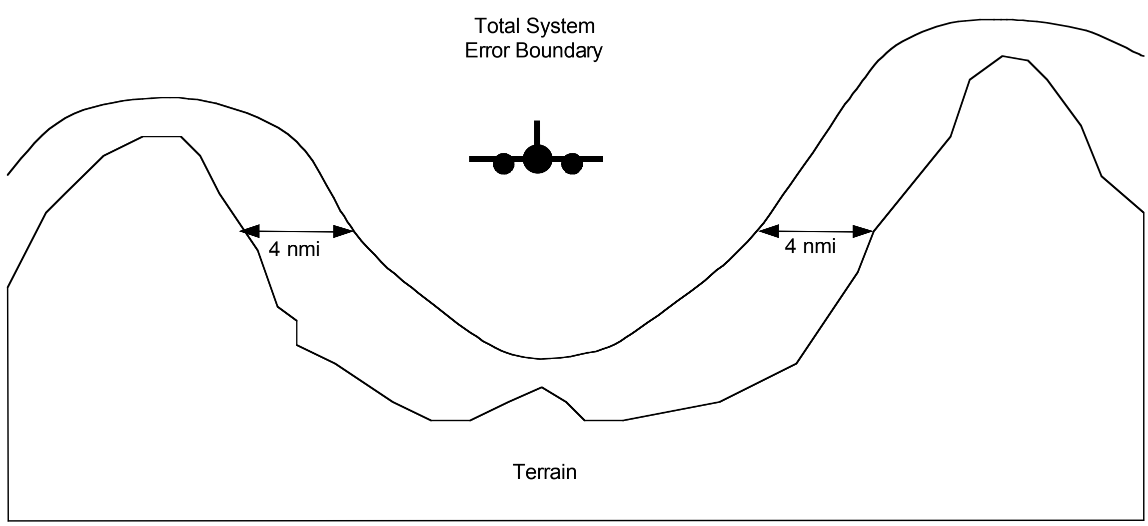


Figure 2-7 Terrain Clearance Requirements (FAR 91.177)

Assuming that terrain separation standards in IFR flight remain unchanged, then the 4 nmi terrain clearance buffer bounds the amount of terrain database uncertainty and the aircraft's navigation capability / uncertainty (e.g., RNP) that can be accommodated. With GPS navigation, aircraft navigation performance of RNP ~1 nmi can be expected. This allows an allocation of ~3 nmi to terrain database uncertainty. Terrain uncertainty manifests itself as both grid resolution, where the grid point is represented by the highest elevation within the grid boundary, and the horizontal accuracy of the location of the grid point itself. Thus it is recommended that enroute terrain grid spacing be at least 150 arc-seconds (~2.5 nmi) with a horizontal accuracy of 1000 meters.

If the goal is to reduce terrain separation standards due to greater capability of terrain database resolution / accuracy and aircraft RNP then it becomes an economic and availability issue on what can be achieved. Since the National Imagery and Mapping Agency (NIMA) Digital Terrain Elevation Data (DTED) level 0 data will provide global 30 arc-second (~0.5 nmi or ~1 km) grid spacing elevation data and horizontal accuracy of ~ 130 meters, this will be more than adequate for enroute operations. Thus Table 2-8 provides a range from 30 arc-second to 150 arc-second data for enroute as the terrain resolution requirement along with a horizontal accuracy requirement of 130 to 1,000 meters.

Obstacle Database Requirements

In determining obstacle database requirements, certain accuracy parameters may be applied to construct buffers around obstacles. However, depending on the radius specified, unrealistically large or converging / overlapping buffers may be generated, resulting in high false alarm conditions. In order to conduct operations in areas near airports using SVS, it is suggested to use obstacle accuracy data as used by the FAA in surveying airport obstacles (Standards for Aeronautical Surveys, FAA No. 405, September, 1996). Table 2-10 summarizes obstacle database accuracy recommendations / requirements. Figure 2-8 provides the Obstruction Identification Surfaces (OIS) in FAR 77 that identify the terrain / obstacle clearance floors used around airports for illustration purposes. OIS and surveyed obstacles are typically used in the development of engine-out takeoff procedures.

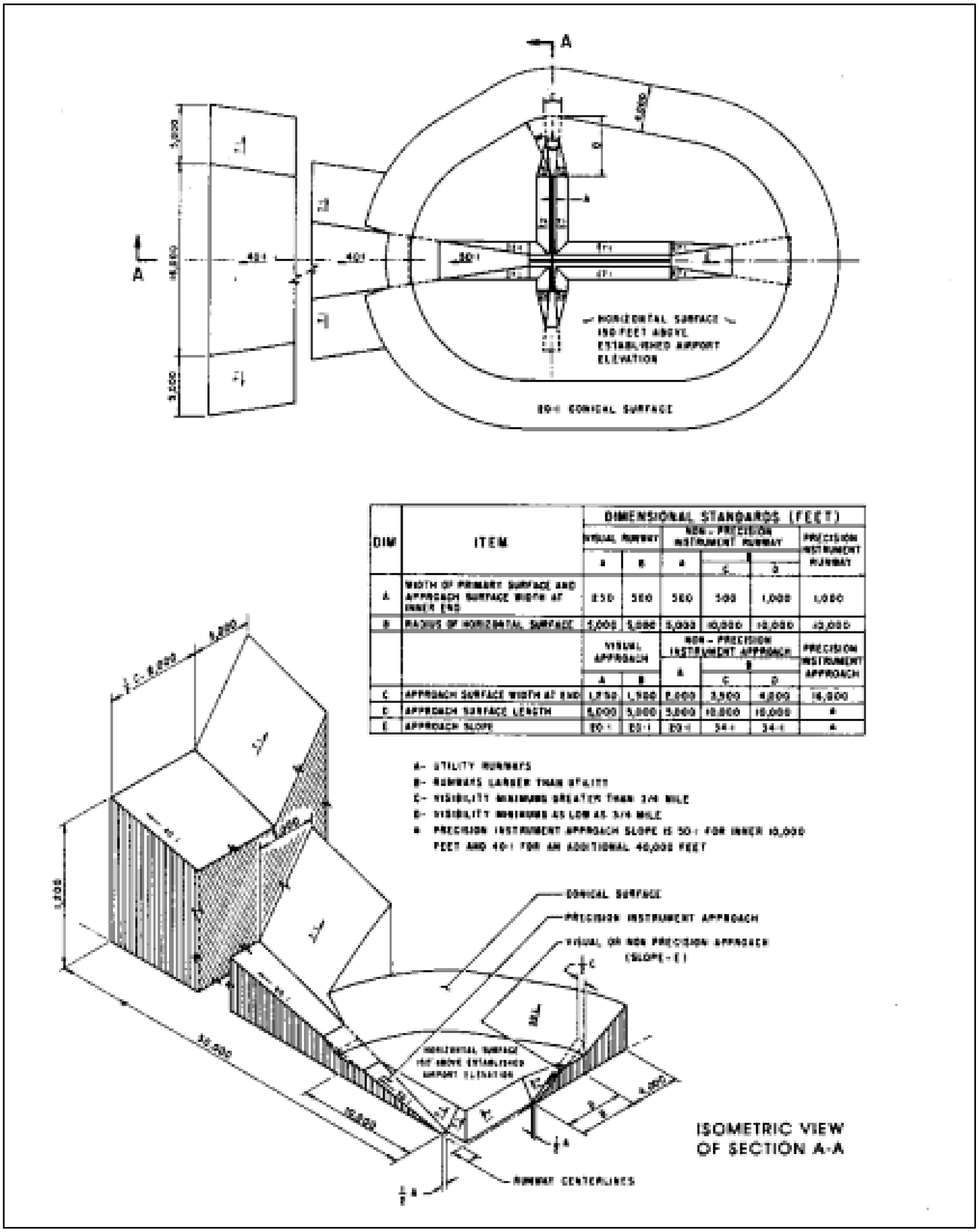
Obstacle Data	**Airport**	**Takeoff / Landing ***	**Departure / Approach ***	**Enroute ****
Resolution	N/A	N/A	N/A	N/A
Horizontal Accuracy	1 meter	20 feet	50 feet	130 meters
Vertical Accuracy	1 meter	3 feet	20 feet	30 meters
Confidence	95%	90%	90%	90%

* Based on NGS, FAA 405 accuracy standards
** Based on NIMA DTED Level 1 accuracies

Table 2-10 Obstacle Database Requirements

Cultural Features Requirements

Cultural features can consist of a wide range of objects that supplement terrain and obstacle data in order to provide a more realistic synthetic vision view. Cultural features are most beneficial to general aviation pilots in all flight phases, and may also be beneficial to air transport operators in terminal area operations, i.e., low-level flight regimes. It is recommended that cultural features be limited primarily to roads, rivers, and railroads. Inclusion of other extraneous cultural features, e.g., trees, etc. may provide excessive clutter to the SVS display. Optimum use of cultural features requires further study.



DIM	ITEM	DIMENSIONAL STANDARDS (FEET)					
		VISUAL RUNWAY		NON - PRECISION INSTRUMENT RUNWAY			PRECISION INSTRUMENT RUNWAY
		A	B	A	B C	B D	
A	WIDTH OF PRIMARY SURFACE AND APPROACH SURFACE WIDTH AT INNER END	250	500	500	500	1,000	1,000
B	RADIUS OF HORIZONTAL SURFACE	5,000	5,000	5,000	10,000	10,000	10,000
		VISUAL APPROACH		NON - PRECISION INSTRUMENT APPROACH			PRECISION INSTRUMENT APPROACH
		A	B	A	B C	B D	
C	APPROACH SURFACE WIDTH AT END	1,250	1,500	2,000	3,500	4,000	16,000
D	APPROACH SURFACE LENGTH	5,000	5,000	5,000	10,000	10,000	*
E	APPROACH SLOPE	20:1	20:1	20:1	34:1	34:1	*

A- UTILITY RUNWAYS
B- RUNWAYS LARGER THAN UTILITY
C- VISIBILITY MINIMUMS GREATER THAN 3/4 MILE
D- VISIBILITY MINIMUMS AS LOW AS 3/4 MILE
* PRECISION INSTRUMENT APPROACH SLOPE IS 50:1 FOR INNER 10,000 FEET AND 40:1 FOR AN ADDITIONAL 40,000 FEET

Figure 2-8 Airport Obstacle Identification Surfaces

Airport Database Requirements

Airport databases play an important role in the SVS surface operations applications, where flight crews use the displayed airport database information for situational awareness of the surface environment, strategic taxi planning, and perhaps even for tactical guidance in low-visibility weather. This requires database accuracies on the order of 1 meter or less. Unlike terrain databases, which are typically represented as grid points with associated by elevation data, airport databases are typically constructed from a photogrammetric image that is then converted to vectors and assigned themes and attributes using Geographic Information Systems (GIS) techniques. Issues concerning airport databases are further discussed in Section 3.

Navigation Database Requirements

Navigation databases are currently used by the FMS to provide flight planning and area navigation capabilities. Navigation databases can also be used to supplement / complement SVS terrain / obstacle display data with pertinent navigation information, e.g., cockpit display of electronic flight charts. Current navigation databases meet the information requirements for the envisioned SVS applications. Database integrity will be an issue as data (navigation and all other SVS databases) are used for the more flight critical SVS applications. Current navigation and other SVS databases are of insufficient integrity to support applications that are essential or of higher criticality.

Note: For all SVS databases, in addition to storing the basic information elements in each database, the databases should also indicate the available data integrity. For example, it is quite likely that for the global terrain database, some areas of the database will be of higher integrity than other areas. This integrity information is important for the end user SVS applications. In the event of loss or availability of higher-integrity data, some SVS applications may provide reduced level of operational performance, and some application may not be available to the flight crew if data integrity is inadequate.

Section 3 provides more discussion on SVS database issues.

2.6.6 SVS Applications Processing Requirements

This section discusses requirements associated with the SVS applications processing function (refer to Figure 2-1).

The SVS application processing function is responsible for processing input data from the SVS databases (i.e., the geo-referenced databases, including terrain, and weather, and traffic databases) and inputs from aircraft position and aircraft state sensors. This function provides the basic processing for the various SVS applications (e.g., the SVS applications discussed in Section 2.5, and SVS weather and traffic applications). The SVS applications processing function must be capable of managing multiple applications that may have different levels of integrity / criticality of function. The SVS application processing function also performs the processing associated with outputting the information to the display manager / graphics rendering / image fusion function (Figure 2-1) that is discussed in the next section. The outputs will be in the form of high-level graphics directives designed for a standardized / common graphical application interface.

SVS applications processing must have the capability to detect when a loss or reduction of data integrity occurs for data associated with the SVS information databases. Depending on the data integrity that is available, the SVS applications processing function must determine the level of SVS applications that can be supported and must notify the flight crew of any reduced capability in SVS services.

From an implementation perspective, the SVS applications processing function may be implemented as an integrated system or may be partitioned among a number of avionics systems. When multiple applications are integrated in one system, it is important to provide appropriate functional / integrity partitioning among both hardware and software components to ensure that lower integrity SVS safety system applications do not inadvertently corrupt higher integrity SVS tactical applications. Of course the hardware system must also provide adequate computational and memory storage requirements to accommodate the range of SVS applications that are desired.

2.6.7 Display Manager / Graphics Rendering / Image Fusion Requirements

This section examines requirements of the display manager / graphics rendering / image fusion functional block shown in Figure 2-1.

The display manager function receives high-level graphics directives from the SVS applications processing function, preferably using a standard / common graphical application interface. Information flowing across this interface will represent a range of information types, e.g., geometric data, raster / bit map data, etc. It is the role of the display manager system to prioritize the information to be displayed and layer the information appropriately for graphics rendering. Depending on the number and types of displays used, a display manager function will be dedicated to each type of display.

The graphic rendering function provides the processing of the information that is selected by the display manager. This processing performs the necessary transformations, etc. to generate the display bit map data. There may be several graphics rendering functions active when several SVS applications are concurrent. The outputs of the graphics rendering functions are output to the image fusion function, which merges various graphics renderings into a single graphics output for each type of display. Section 3 provides additional discussion concerning SVS database architectures and graphics generation issues.

2.6.8 Display Requirements / Considerations

This section discusses SVS display requirements. As indicated in the previous section, the display manager / graphics rendering / image fusion function provides a fused image to be presented for each type of flight deck display. The following display types may play a role in SVS:

- Head-up display (HUD)
- Primary flight display (PFD), attitude direction indicator (ADI)
- Navigation display (ND), multi-function display (MFD), Horizontal Situation Indicator (HSI)
- Side-display
- TCAS display, weather radar display
- Standby instrument display

The type of flight deck display used to portray SVS information is dependent on the originating SVS application. Since tactical SVS applications require the flight crew's immediate (i.e., low-latency, low head-down time) attention, most appropriate displays for these applications are the HUD and PFD / ADI displays. Strategic SVS applications provide a more situational awareness, strategic planning capability, which typically is associated with ND / MFD / HSI type displays. A side-display and standby instrument display may also be considered for SVS strategic applications. When the cost of retrofitting PFD and ND displays for SVS is excessive, side displays may offer the only available option for retrofit of SVS capability. Section 4 more closely examines the aircraft equipage and retrofit issues related to SVS.

One of the significant issues for high-end air transports and aircraft used by business and regional operators is the relatively limited graphics capabilities of current cockpit displays. To support future SVS applications, new SVS cockpit displays will require significantly greater graphics capability.

Current state of the art for graphics generation from a terrain display perspective is the ability to render ~1 million triangles / second (of course these numbers continue to increase as technology advances). For a frame rate of 30 Hz, this allows ~30,000 triangles / second to be processed. For stroke CRT displays, ~ 400 inches of stroke vectors can be painted per second, while ensuring sufficient brightness of display vectors. Further increases in stroke rate begins to reduce brightness.

For SVS safety system applications, the display requirement consists of a minimal plan view / map mode on a ND / MFD display. Colors are used to depict terrain below / above current aircraft altitude. This is similar to the EGPWS type of display. As a market discriminator, SVS safety system displays can be extended to provide: 1) 3-D PFD / HUD terrain display, and 2) terrain escape guidance. However, these additional capabilities are outside the realm of safety system applications and <u>increase the criticality of the system</u>.

For SVS strategic guidance applications, a minimum display requirement is for a 2-D plan view ND / MFD display. This can be upgraded to 3-D perspective display on a ND / MFD display with a depiction of a 3-D flight plan with terrain information. This could further be extended to a 3-D perspective display on a PFD / HUD, although this would probably be considered as a tactical display.

SVS tactical applications may require a 3-D perspective display on a PFD / HUD with pathway-in-the-sky cues.

<u>SVS Displayable Information</u>

The optimum use and integration of SVS information elements and associated display formats will require considerable human factors studies and will not be addressed here. The following information elements are listed as those important to the SVS applications identified previously:

- Terrain
- Obstacles
- Airport
- Cultural features
- Navigation data
- FMS data
- Navigation data
- (Aircraft) performance data
- Conventional PFD display data
- Conventional ND / MFD display data
- HUD display data
- Aircraft attitude

- Aircraft trend vector, predicted trajectory
- Radar data (terrain mapping, terrain image)
- Vision sensor data
- SUAs, PIREPS, NOTAMS, CPDLC datalink messages, FIS-B / FIS.

SVS Information Display Formats

The above information elements may be integrated in a variety of combinations and formats to provide optimum SVS information to the flight crew. A number of display formats and display views may be considered for SVS displays. Again, optimum display formats for SVS require human factors study and will not be addressed here. Some display formats / viewing perspectives to be considered are listed:

- Conventional alphanumeric displays versus intuitive displays
- Pathways-in-the-sky display formats and viewing perspectives
- Fly-the-Image display formats and viewing perspectives
- Strategic flight path information formats and viewing perspectives, e.g., 3-D FMS strategic display (flight plan, flight path, 3-D terrain, weather / lightning data, traffic information, navigation data, cultural features, etc.)
- 2-D plan view FMS display (flight plan / map mode / plan mode, flight path / trend vector, terrain contours, weather, traffic, navigation data, airport data, cultural features, etc.)
- 2-D vertical view of flight path and terrain profile
- Combination of 2-D plan view with an inset of a 2-D vertical view of flight path.
- Etc.

The above display formats / concepts represent a wide range of SVS display capability. As will be discussed in Section 4, retrofit of SVS applications into existing cockpit displays is expected to be a difficult problem due to the limited display graphics capabilities of the current aircraft fleet. A display format that uses a combination of a 2-D plan view with an inset of a 2-D vertical view of the flight path represents a potentially promising retrofit candidate for cockpit displays for aircraft equipped with EFIS-type displays (refer to the discussion of EFIS equipped aircraft in Section 4.2). Further study is required to determine if this retrofit option is viable for these aircraft.

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Sample SVS Display Formats

The following display formats are provided for illustration purposes. Again, the most appropriate display for the various SVS applications requires further study.

For reference, the EGPWS Terrain Display in Figure 2-3 is repeated below in Figure 2-9. This figure represents the current SVS display baseline used by EGPWS. It represents a 2-D plan view of the aircraft flight path with terrain depicted in shaded colors to indicate terrain that is either above or below the aircraft altitude. This display is only intended to provide situational awareness information and should not be used for guidance due to the relatively low system integrity of this safety system. The actual display used by EGPWS is the weather radar display.

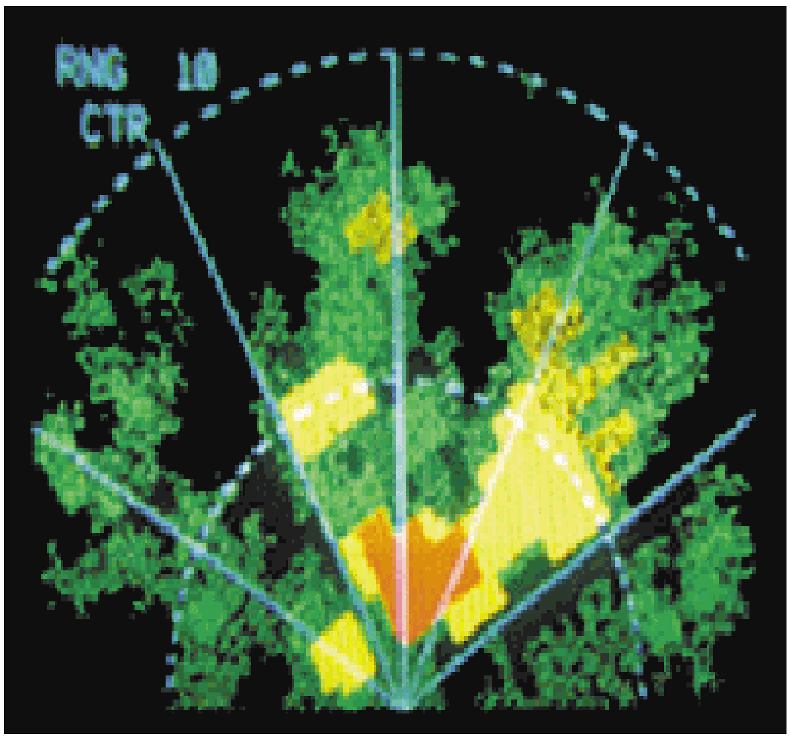

Figure 2-9 EGPWS Terrain Display

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Relative to the situational awareness terrain display used by EGPWS, Figure 2-10 provides a conceptual display of SVS information that is important to the flight crew. Figure 2-10 shows a 3-D display concept that integrates the fundamental SVS information elements of terrain / obstacle data, cultural features such as roads, trees, etc., other traffic, hazardous weather, and the 3-D flight plan with associated waypoints.

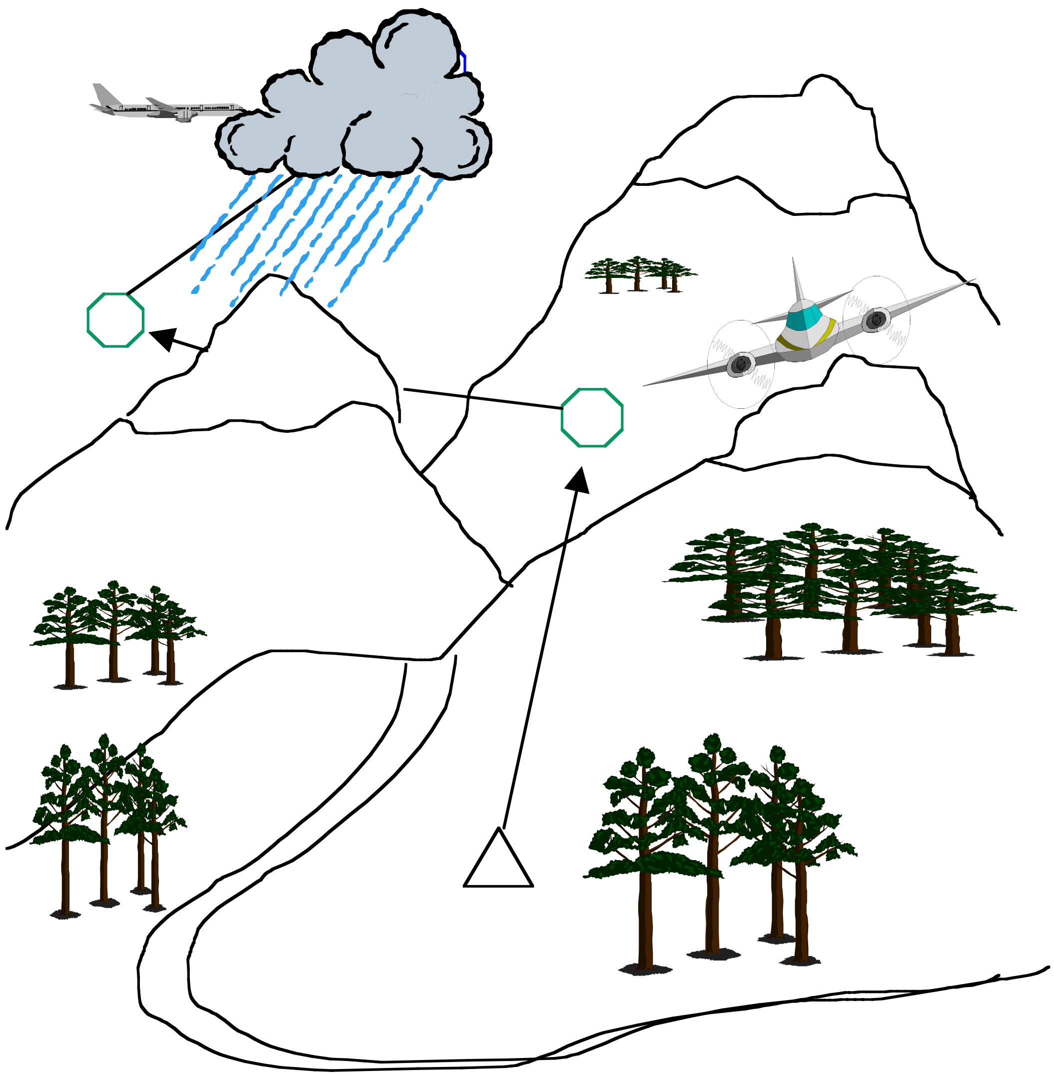

Figure 2-10 Conceptual Synthetic Vision System Display

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Figure 2-11 provides an illustration of a 3-D flight management system display that depicts the location of the aircraft and its associated flight plan / intended path (including waypoints). Also shown are vertical limits to the flight plan. These vertical limits may be constrained by traffic (as shown to the left of the flight path in close proximity of own aircraft position), or could also be constrained by terrain or other potential hazards. This display does not show any terrain. However, an SVS strategic planning application could be providing terrain safe flight planning, and could ensure that the flight plan is terrain safe. Of course, terrain could also be integrated into the 3-D flight management display.

Figure 2-11 3-D Flight Management System Display Concept

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Figure 2-12 shows a combination display that provides a 2-D plan view, track-up terrain display at the top with a 2-D vertical view of terrain inserted at the bottom of the display. The plan view is typical of ND / MFD displays. The terrain is color coded to indicate elevation.

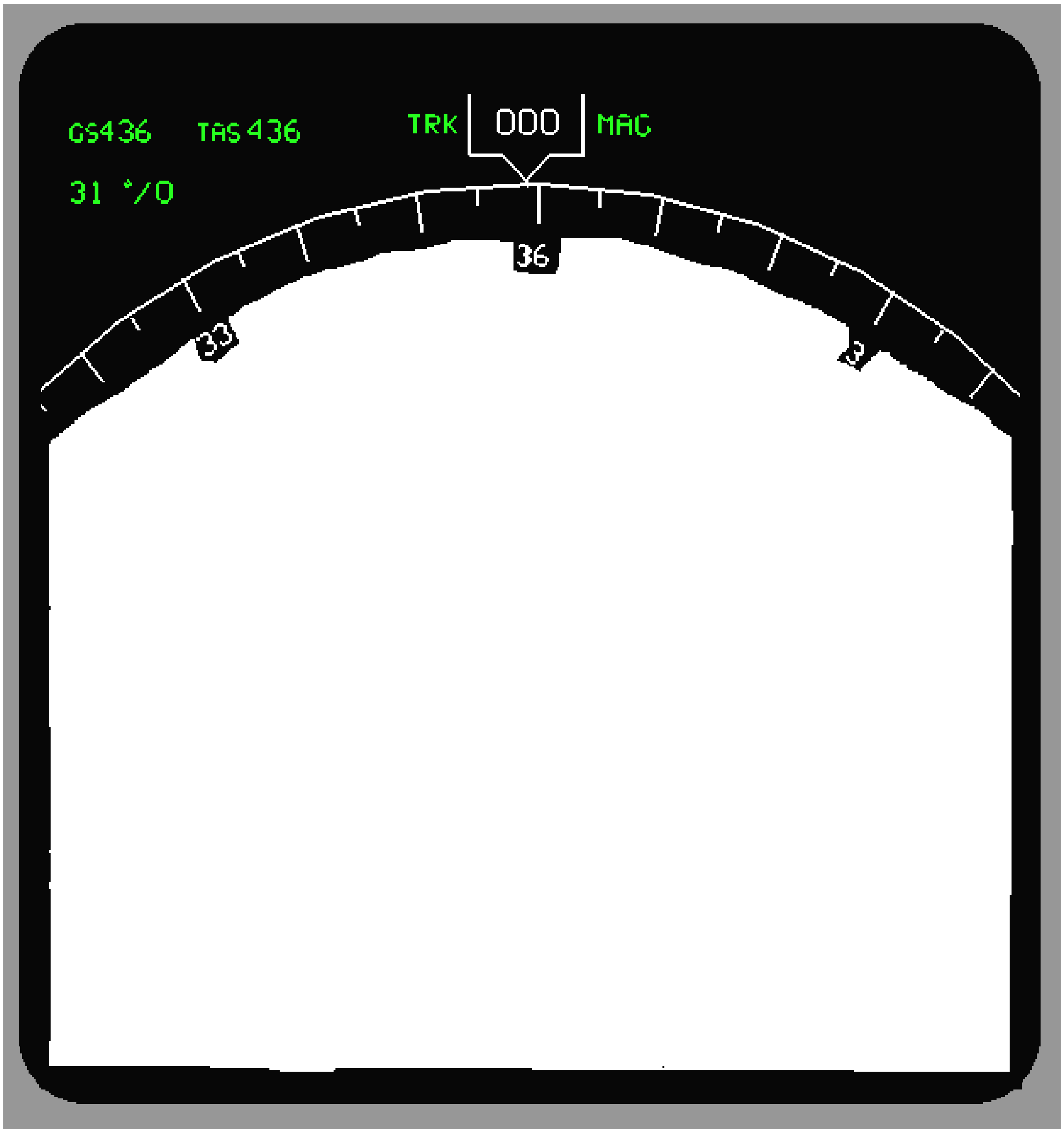

Figure 2-12 2-D ND / MFD Terrain Display

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Figure 2-13 provides a similar terrain display as shown above except in a 3-D perspective view and is integrated in a PFD display that also indicates typical PFD data such as airspeed, altitude, and precision guidance information (localizer and glideslope deviaitons).

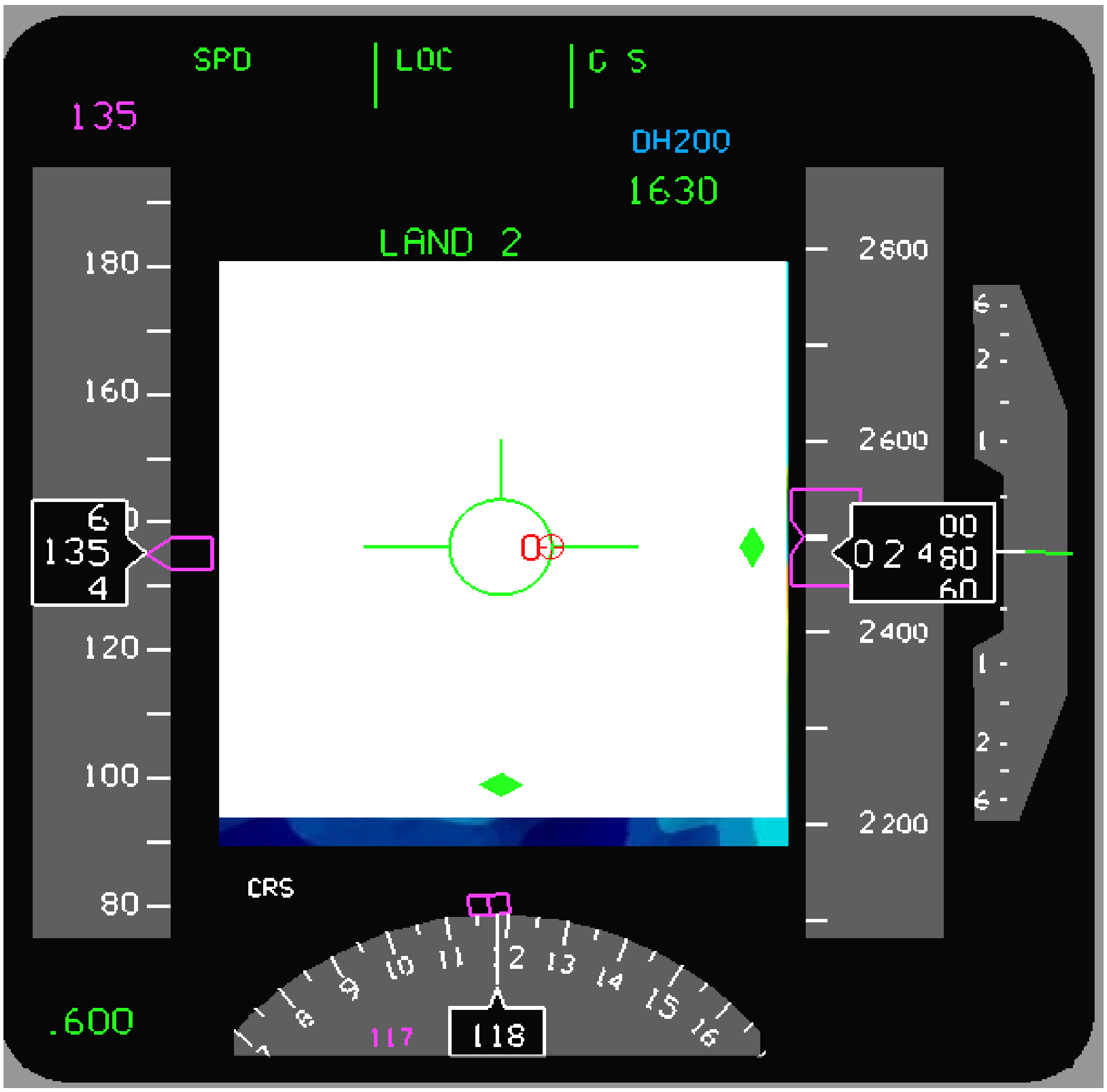

Figure 2-13 3-D Perspective View Terrain Contour Format on PFD

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Figure 2-14 illustrates another 3-D perspective view display of terrain on a PFD display, except that instead of colored terrain contours, this display uses a realistic representation of terrain.

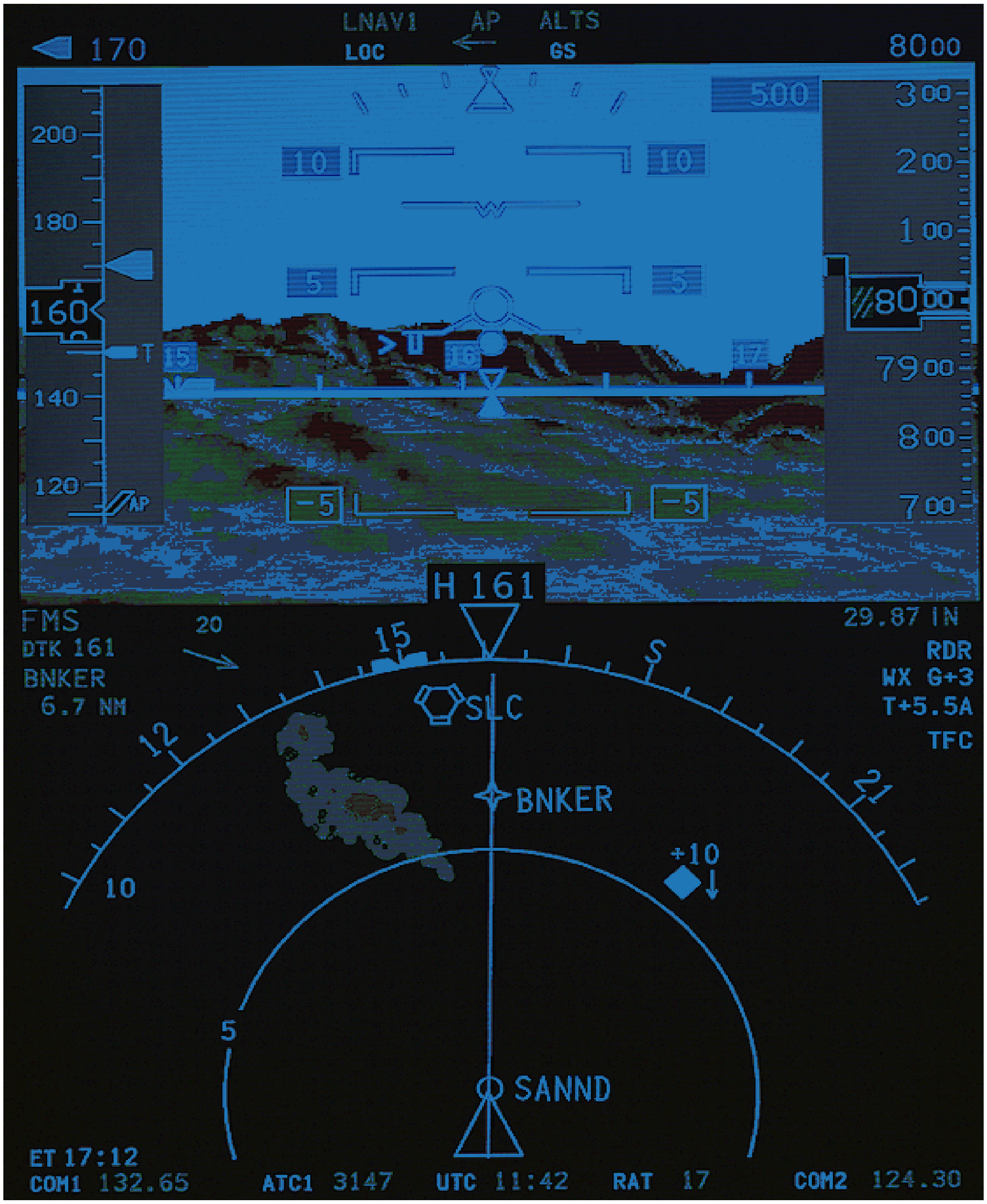

Figure 2-14 3-D Perspective View Realistic Terrain Format on PFD

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Figure 2-15 shows a 3-D perspective terrain display that also combines a pathway in the sky and associated guidance commands.

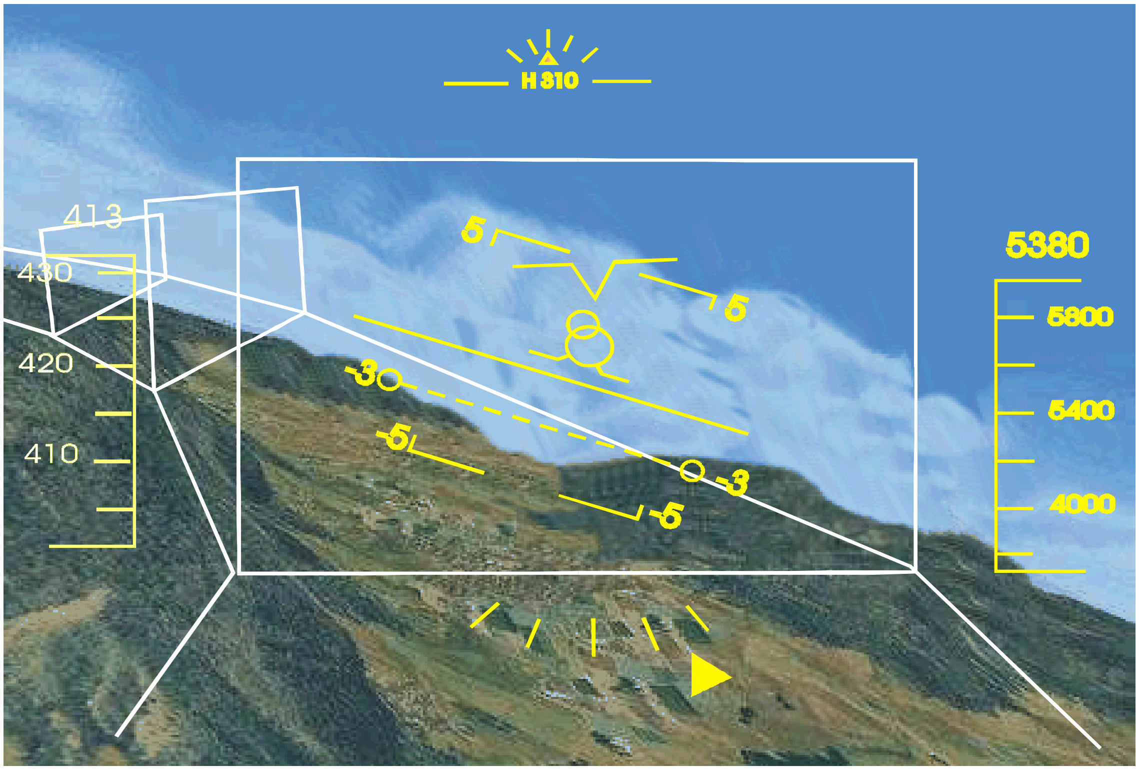

Figure 2-15 3-D Perspective Terrain Display with Pathway-in-the-Sky Guidance

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Unlike the previous displays, the display shown in Figure 2-16 represents a 3-D perspective view display of an airport layout for surface taxi operations. In addition to a high precision airport database, the figure also depicts own aircraft position, the planned taxi route, stop bars that reflect the extent of taxi route clearance, runway holdbars that indicate when a runway is active, and other traffic. This display was developed by NASA as part of the Low-Visibility Landing and Surface Operations (LVLASO) program and was tested and demonstrated at the Atlanta's Hartsfield in 1997. This display was implemented as a head-down display and would likely be integrated onto the ND / MFD display for taxi operations. This display also indicates the runway incursion prevention benefits of a pilot being aware of the airport surface traffic environment.

Figure 2-16 LCD Taxi / CDTI Display

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2.7 Key Synthetic Vision System Applications Issues

2.7.1 Criticality of System Is Application Dependent

The safety system, strategic, and tactical applications each have an integrity requirement base on the systems failure effects as discussed in Section 2.5.1. There are several issues related to the level of integrity requirements.

Application Enhancements

System enhancements may cause the criticality and thus the system integrity requirements of the system to increase. For example, if a 3-D PFD / HUD terrain display or terrain escape maneuver is added to a TAWS system as a market discriminator the system will become essential or critical respectively.

Inappropriate Unintended Use

Unintended use is a case where a system is used for an application for which it is not designed. For example the flight crew must not use a TAWS display for strategic or tactical flight, since the underlying system (e.g., the terrain database) is of insufficient integrity to allow such operations. This is a significant issue, which is further exacerbated when the terrain display is further improved to provide a realistic, high quality appearance of the terrain.

Database Integrity Effect on Applications Integrity

A significant issue for SVS applications is the integrity associated with the SVS database. The SVS integrity is directly impacted by the integrity of the source data (see Section 2.6.3). If the source data has inadequate integrity (i.e., contains some undetected errors), then the SVS also has inadequate integrity.

2.7.2 Data Base Integrity Issues

High Integrity Databases

Tactical SVS applications require very high system integrity. Due to the expected problem of achieving very high SVS database integrity, it is likely that SVS application will be hard-pressed to achieve ~10^{-9} unannunciated loss-of-function / misleading information requirement for terrain and obstacle data. In that event, it may be necessary to have a second, completely independent, database to compare with the first. Since two completely independent sources for the required databases may not be feasible other means are required to corroborate the terrain databases.

Independent Position Determination / Verification may be possible using a ground mapping mode of weather radar. In this case ground based radar reflectors may be required on certain terrain features to enhance the accuracy of the radar mapping. The reflectors might be placed on significant terrain features of interest to aircraft or at key points on the airport surface to define the airport location and layout. Another possibility is to use a transponder based position determination. The transponders could be located similar to the radar reflectors. The transponders could transmit their GPS position similar to ADS-B position. An alternative would be to use multilateration between the aircraft and multiple transponders. Other independent database verification methods may also be possible.

Applications Need To Know Integrity of Database in Real Time

In addition to storing the basic information elements in each database, the databases must also indicate the level of the stored data. For example, it is quite likely that for the global terrain database, some areas of the database will be of higher integrity than other areas. This integrity information is important for the end user SVS applications. In the event of loss or availability of higher-integrity data, some SVS applications may provide reduced level of operational performance, and some applications may not be available to the flight crew.

2.7.3 Human Factors Issues

There are many human factors issues that will need to be addressed for SVS. The Literature Review in Appendix A touches on some of these factors. The list below gives a sample of the human factors issues that will need to be addressed.

- What information is appropriate for display
- What combinations of information should be displayed / display modes
- What formats and graphical depictions are most appropriate
- Integration of various information sources for display purposes
  - SVS terrain / obstacles / cultural features / airport data / navigation data
  - Traffic information
  - Weather
  - Other information such as SUA, volcanic ash, data link messages, etc
- Strategic versus tactical versus safety / hazard display information depiction
  - Which displays for which information?
  - Information layering, level-of-detail needed, zoom levels, display modes
  - Display formats, type of depiction/rendering (2-D, 3-D other)

2.7.4 Navigation / Precision Approach versus SVS

SVS Navigation

SVS for navigation purposes is likely not technically and economically feasible compared to other navigation systems (GPS navigation and / or pathway displays) for precision approach and enroute navigation

Pathway for Precision Approaches versus SVS

Since precision approaches are very safe and provide protection from CFIT and loss-of-control accidents, it is not clear what the appropriate role of SVS is relative to the use of precision approaches to eliminate these types of accidents. It is not obvious that displaying the terrain / obstacle hazards to the crew would be better than just using the database to generate a guided departure flight path using a pathways-in-the-sky pathway. The benefit to the SVS appears to be in blunder or emergency situations when the standard path was not or could not be followed, especially in obstacle rich environments like Juneau, Alaska.

2.7.5 Operational Benefits

Reduced Separation Standards

The current IFR terrain separation standards were developed to allow for errors in terrain maps and also to account for typical aircraft navigation capability supported by current navigation aids. More airspace will be available for “free flight” if the separation standards can be reduce because of accurate terrain databases and aircraft SVS capabilities for strategic and tactical flight guidance. The safety of operations with reduced terrain separation standards needs to be investigated. If reduced terrain separation operations are save, the government regulations (FARs) will need to be changed to them.

Reduced Approach and Landing Minimums

The operational cost benefits and technical feasibility of the SVS approach monitor application (Section 2.5.4.1) requires further study. Table 2-2 is offered as an overview of visibility limits (runway visual range, RVR, and decision height, DH) for precision approach and landings. The limits for SVS with and without a head-up guidance system need to be established in order to determine the potential operational benefit.

The operational cost benefits and technical feasibility of the SVS approach and landing aid application requires further study. Table 2-3 provides an overview of taxi visual aid requirements in terms of taxiway lighting / reflectors, etc. It is to be determined how SVS can be used in the flight deck as an approach and landing aid to possibly reduce the need for airport lighting / signing / marking infrastructure.

2.7.6 Integration of Functions and System Partitioning

From an implementation perspective, the SVS applications processing function (Section 2.6.6) may be implemented as an integrated system or may be partitioned among a number of avionics systems. When multiple applications are integrated in one system, it is important to provide appropriate functional / integrity partitioning among both hardware and software components to ensure that lower integrity SVS safety system applications do not inadvertently corrupt higher integrity SVS tactical applications.

2.7.7 Display Retrofit

A combination of a 2-D plan view with an inset of a 2-D vertical view of flight path may offer the best potential candidate for retrofitting SVS display capability into existing EFIS display equipped aircraft.

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3.0 Synthetic Vision Databases

Section 2 addressed synthetic vision system (SVS) applications concepts and identified top-level SVS requirements, including requirements for the SVS geo-referenced databases. This section focuses entirely on the SVS geo-referenced databases of terrain, obstacles, cultural features, airport, and navigation. Section 3 is organized as follows:

- Section 3.1 provides a database glossary of common database terms.
- Section 3.2 provides a brief overview of currently used avionics databases that pertain to SVS and compares them to SVS databases needed for future applications.
- Section 3.3 is a survey of database providers and database capabilities. In this section database availability is examined, along with issues associated with the acquisition, validation, management, certification, and distribution of these data. This section also provides recommendations for mitigating the issues or highlighting any significant issues that could have an impact in implementing acceptable solutions. A database implementation plan is also offered.
- Section 3.4 addresses issues pertaining to SVS database architecture and takes a top-level look at the SVS graphics generation problem.
- Section 3 concludes with a summary of key SVS database issues in Section 3.5.

3.1 Database Glossary

Accuracy — The confidence that the true ground elevation is within a specified tolerance, usually expressed in meters with 90% confidence for the appropriate distribution. Accuracy consists of two components: bias, which is the combined horizontal and vertical offsets from the real-world reference; and RMS Error, which is the limit of the measuring system to detect changes in terrain elevation.

Bias — A component of the overall accuracy for an individual elevation point. Bias is determined by comparison to known points and can be evaluated only in selected regions of the world where high quality data is available for the analysis.

Cyclic Redundancy Check (CRC)

A mathematical algorithm applied to bits of data typically applied during data processing that provides a level of assurance against loss or alteration of the data during storage or transmission of data.

Database — One or more electronically stored files of data so structured that the files can be electronically accessed by computer for appropriate applications, use and / or update.

Elevation Data — Values representing the ellipsoidal or natural height above mean sea level at a given location. This is not intended to include man-made features or tree tops.

Geodetic Datum	The numerical or geometrical quantity or set of such quantities (mathematical model) which serves as a reference for computing other quantities in a specific geographic region such as the latitude and longitude of a point.
Geoid	An equipotential gravitational surface which coincides with the undisturbed mean sea level (MSL) over the oceans and its extension under the continents. Elevations called orthometric heights are determined in relation to the geoid. Note that the geoid is irregular in shape because of local gravitational disturbances.
Grid	A representation of a rectangular area typically defined with evenly spaced rows of data and evenly spaced columns of data within each row.
Grid Resolution	The distance between elevation posts within a grid. This is synonymous with grid interval. A constant interval value is used between the rows and columns of a grid.
Ground Control Points	Identifiable positions on the ground which have a known and highly accurate latitude, longitude and elevation. These points are used often for validation purposes of other terrain data sets and to properly correlate or align an existing data set. (GCP).
Kriged Error Variance	A value that represents the variability for a given area surrounding a specific elevation point.
Multi-variate Kriging	A mathematical process that performs a statistical interpolation between different data sets to produce a Digital Elevation Model, or a grid of elevation data. The Kriging interpolation process produces the Best Linear Unbiased Estimate (BLUE) as well as a known error value, otherwise known as the Kriged Error Variance.
Obstacles	Man-made features built on top of the terrain that could have an impact on navigation.
RMS Error	Root Mean Square error, a component of the overall accuracy for an elevation point. (see Accuracy)
Terrain	Terrain refers to the representation of the natural features associated with the earth's surface. This is not intended to include man-made features or tree tops.
Validation	The activity whereby a data item is checked as having a value which is fully applicable to the identity ascribed to the data item, or a set of data items is checked as being acceptable for their purpose. Validation checks are often confused with verification checks. Validation checks include range limit checks, related record / field checks and data item relationship checks. Data item checks, including colinearity checks, elevation checks and geographical vicinity checks, are also considered to be validation checks.

Verification	The activity whereby the value currently accorded to a data item is checked against the value originally supplied. Verification is a process for checking the integrity of a data item. It usually takes place when data are input to a database where it can take the form of a visual check of input data against the original source document by an independent checker or an automatic check of the same data which is entered two or more times by one or more data entry operators. Re-computation and confirmation of CRC values is a form of verification check.

3.2 Current State-of-the-Art of Avionics Databases

This section discusses the current use of avionics databases in operational and planned systems. FMS navigation, EGPWS / GCAS terrain, and LAAS final approach segment (FAS) databases represent avionics databases that are currently being used in existing or planned avionics systems. Air traffic controllers utilize terrain information to provide minimum safe altitude warning (MSAW) to aircraft under surveillance radar control. It is beneficial to compare and contrast these current / planned systems, to assess their potential use for SVS applications.

3.2.1 FMS Navigation Database

Aircraft have long been using an aeronautical navigation database in their flight management systems (FMS). ARINC 424 identifies information requirements for the navigation system database. This database includes information concerning air routes, navigational aids, etc. FMS systems have typically been placed into the non-essential category (~10^{-3} to 10^{-5} probability of undetected failure / error). Accordingly, <u>the navigation database is also of relatively low integrity</u>. Navigation database information is provided by the FAA as part of the development of air route navigation procedures. <u>The navigation database is assumed to be correct</u> based on the procedures that are developed, but it can certainly not be viewed as high-integrity data. Future use of FMS for advanced navigation (RNP, etc.) will likely necessitate an increase in system criticality to essential, including the navigation database.

3.2.2 EGPWS / GCAS Terrain Databases

Both EGPWS (TAWS) and GCAS systems specify a system integrity of 10^{-5} probability of undetected failure of any system component per flight hour, which also includes the associated terrain databases. This is typical of SVS safety system applications. As indicated in Section 2.6.3 (Figure 2-4), terrain database integrity has an unmitigated impact on system integrity, since any undetected failure in the database source data itself directly compromises system integrity. Thus the EGPWS / GCAS safety system terrain database integrity is also on the order of ~10^{-5}.

While TAWS and GCAS require 15 arc-second and 30 arc-second terrain grid resolution within 15 nmi of the airport and the terminal area, respectively, oceanic and remote area terrain data requires only 300 nmi and 5 nmi grid spacings, respectively. Future SVS applications, will likely require higher resolution terrain data for oceanic and remote areas, perhaps even to 30 arc second spacing provided by National Imagery and Mapping Agency (NIMA) Digital Terrain Elevation Data (DTED) level 0 terrain data. The actual resolution requirement depends upon how aggressively the industry wants to exploit improved RNP navigation and terrain data to reduce current terrain separation standards (if at all).

3.2.3 LAAS Precision Approach Database

The local area augmentation system (LAAS) is currently being developed and is intended to support precision approach and landing operations (i.e., Cat I, Cat II and ultimately Cat III) and other navigation and surveillance operations within a local area surrounding an airport. The LAAS ground station monitors the performance of satellites and uplinks differential corrections and satellite status information via datalink to airborne receivers. This information is used to provide the navigation and surveillance information and the associated system integrity. In addition, the LAAS ground station uplinks the precision approach navigation database that consists of data, which defines the precision approach paths to all the approaches, serviced by the LAAS facility. LAAS approach path data is referred to as Final Approach Segment (FAS) data.

As a precision approach system, LAAS is categorized as a critical system with an integrity requirement of 2×10^{-7} / approach for Cat I and 10^{-9} / approach for Cat II / III. The LAAS precision approach path database must have an integrity level somewhat greater than the overall LAAS system, since other system components also contribute to the integrity budget. Thus, the LAAS precision approach (i.e., waypoints) navigation database is the first example of an avionics database that is critical in nature.

The precision approach path lateral and vertical deviation budgets include the total system error associated with the LAAS / DGPS navigation system. Total system error consists of navigation system error and flight technical error (i.e., errors associated with the pilot's ability to fly to the navigation guidance signal). Also to be included in the deviation budgets are the errors associated with the FAS data. For LAAS, errors in the FAS data are judged to be acceptably small and thus do not contribute significantly to the deviation budgets. The intent is for the FAA to provide highly accurate, high integrity FAS data via high accuracy airport surveys and extensive flight testing of the precision approach system to validate the FAS data.

The FAS database message that is uplinked to the aircraft is encoded using a cyclic redundancy code (CRC) error correction / detection code. This code is very robust and provides the needed integrity monitoring to minimize the possibility of undetected errors of the FAS data, that are critical to the precision approach.

In summary, LAAS is an example of a system that uses a critical avionics database. This database is very small (especially, when compared to terrain data), consisting only of a few FAS data for each runway. The needed integrity is achieved through high integrity airport surveys and flight testing of LAAS precision approach. This kind of scrutiny / data integrity process will be very difficult to apply to the development of a high integrity terrain database simply due to the vastness of global terrain that will need to be surveyed. In this regard, the LAAS example will not be of help in terms of process for future development of high-integrity terrain data.

3.2.4 MSAW Terrain Database

Unlike the above systems, which are primarily avionics based, the Minimum Safe Altitude Warning (MSAW) system is a safety system used by air traffic controllers. Controllers utilize MSAW to provide ground proximity warning alerts in the event an aircraft inadvertently deviates from intended flight plan and is in close proximity to terrain. The aircraft is tracked by the secondary surveillance radar, which derives position, altitude and identification information about the aircraft. Using terrain, obstacle data, and the radar information, MSAW alerts the controller about a threatening situation and the controller then contacts the aircraft via voice radio to alert the flight crew of the hazard.

MSAW terrain data uses 2 nmi grid spacing (i.e., 120 arc-second) data. Data is derived from several sources and is merged into one terrain database. The terrain data uses the highest elevation point of the merged data set using USGS 1:250,000 digital elevation map, 7.5 degree digital elevation data and DTED data. Obstacles that are greater than 200 ft above the ground are also merged into the MSAW terrain / obstacle database. Area coverage of early generation MSAW used 62 nmi radius circles around airports. New MSAW systems typically provide terrain / obstacle warning data for a 160 nmi by 160 nmi square centered at the airport, with some as large as 200 nmi by 300 nmi.

Being a warning system like EGPWS / GCAS, MSAW also has a relatively low integrity requirements ($\sim 10^{-3}$ to 10^{-5} probability of undetected failure). Similarly, the MSAW terrain / obstacle database also has relatively low integrity requirements.

3.2.5 Comparison of Current and Future Avionics Databases

To date, most of the avionics databases (FMS navigation database, EGPWS / GCAS / MSAW terrain databases, etc.) used in current and planned systems are relatively low-integrity databases. In addition, these terrain databases use relatively low-resolution grid spacings in areas away from airports / terminal areas. The only database that is critical in nature is the FAS data used for LAAS precision approaches. The LAAS database is very small and its high integrity is achieved via rigorous surveys of FAS data and subsequent flight test of the LAAS approach path. It may take similar rigor in developing high integrity SVS geo-referenced databases in support of candidate strategic and tactical SVS applications in the future, although for a significantly larger data set.

It should also be noted that the above database systems require only limited cockpit display capability in support of the SVS applications described. EGPWS currently represents the most extensive use of SVS terrain display using a 2-D plan view on a weather radar display.

Tables 3-1 and 3-2 repeat the terrain and obstacle database requirements discussed in Section 2.6.5. These requirements were determined based on the anticipated needs of the candidate SVS applications identified in Section 2.5 (summarized in Table 2-4). The main emphasis is the potential need for considerably greater terrain resolution for the enroute flight phase. Integrity requirements for these databases will also be significantly more stringent, on the order of $\sim 10^{-5}$ to 10^{-9} (typically $\sim 10^{-7}$) for strategic SVS applications and better than 10^{-9} probability of undetected failure / errors in database information for tactical SVS applications.

The next section provides a detailed survey of database providers and associated database capabilities to meet the terrain and obstacle database requirements listed in Tables 3-1 and 3-2, and the other geo-referenced databases used in SVS.

Terrain Data	Airport	Takeoff / Landing	Departure / Approach	Enroute
Resolution	1 meter	6 arc-seconds	30 arc-seconds *	30 or 150 arc-seconds
Horizontal Accuracy	1 meter	30 meter	130 meter	130 or 1000 meter
Vertical Accuracy	1 meter	10 meter	30 meter	100 meter
Confidence	95%	90%	90%	90%

* could increase to 15 arc-second resolution for mountainous airports

Table 3-1 Terrain Database Requirements

Obstacle Data	Airport	Takeoff / Landing *	Departure / Approach *	Enroute **
Resolution	N/A	N/A	N/A	N/A
Horizontal Accuracy	1 meter	20 feet	50 feet	130 meters
Vertical Accuracy	1 meter	3 feet	20 feet	30 meters
Confidence	95%	90%	90%	90%

* Based on NGS, FAA 405 accuracy standards
** Based on NIMA DTED Level 1 accuracies

Table 3-2 Obstacle Database Requirements

3.3 Survey of Database Providers and Database Capability

This section overviews the availability for each of the databases needed to support synthetic vision (terrain, obstacle, airport, navigation, cultural features, etc.), identifies currently and planned sources for these databases, data availability and cost. This section then assesses capabilities and identifies shortcomings of available databases in meeting the requirements of SVS applications.

3.3.1 Data Availability - Overview

The increased use of Geographical Information System (GIS) technology has created a high demand for GIS data, or data with a spatial component. The scope of this demand extends beyond the data itself to issues governing hardware and software, data collection and management, and data storage and transfer.

Standards must be employed in order to reduce the amount of ambiguity that results when there is an abundance of data collection activities and a lack of standardized methods for accomplishing these tasks. As methods are developed for sharing information, costs involved in spatial data acquisition and integration are reduced.

3.3.1.1 Standards for Data Exchange

Data exchange formats differ for every major digital data product distributed outside its native platform, most of which carry only basic spatial information and minimal attributes. Much time has been spent compiling historical / current data and organizing it into comprehensive data sets.

The investment in data is considerable and the need to disseminate this information is a growing concern that has brought about the development of stringent standards for data exchange. This issue has become evident to major data producing agencies of the US Federal government where the development of a standard way to describe and transfer geographic data products has been mandated.

There are three US Federal agencies that are the responsible definition and maintenance authorities for what has become a set of national and international standards for data exchange:

1) The US Geological Survey (USGS) maintains the Spatial Data Transfer Standard (SDTS), a Federal standard used to transfer a variety of digital information, including DLG, TIGER / Line, and GRASS (definitions of these are founded in Section 3.3.1.1).
2) The National Imagery and Mapping Agency (NIMA), formerly the Defense Mapping Agency (DMA), is the guardian of the international military formats which have evolved into a family of exchange standards including Vector Product Format (VPF) and a format for direct access and distribution of DMA's Digital Chart of the World (DCW), currently known as V-Map.
3) The National Ocean Service (NOS) is the developing agency for DX90, the International standard for hydrographic and nautical chart data.

Although each agency worked in open cooperation with each other, resulting standards diverged to meet users' needs. Standardization goals were the same, however the client bases they served were different.

Each of these three standards exemplifies large, complex compilation and dissemination solutions for feature based vector, raster, and matrix formats. Harmonization studies have been done and recommendations made for the next step towards unifying these standards into a larger more comprehensive set of data content and data exchange standards that will adhere to the fundamental guidelines of the Spatial Data Transfer Standard (SDTS).

3.3.1.2 Supported Geo-Spatial Data Formats

The following file formats generated by other mapping systems, either adhering to SDTS type specifications or not, can be converted into GIS themes or layers. These data sets may be composed of a spatial component and attribute data. Each decomposition tool will verify and convert each data component, according to the user's specifications. There are two types of spatial data to be addressed by formatting and conversion tools: vector and image/raster data types. The more prominent formats for possible SVS use are indicated in bold.

<u>Vector Formats Supported</u>

ADS – Automated Digitizing System developed by US Bureau of Land Management

DFAD – Digital Feature Analysis Data developed by DMA/NIMA

DIME – Dual Independent Map Encoding digital version of the US Census Bureau's Metropolitan Map Series

DLG – Digital Line Graph provided by the Earth Science Information Center of the USGS, includes transportation features, hydrography, hypsography (contours), and public land survey boundaries

DXF – AutoCAD Drawing Interchange File interchange format used by CAD systems (i.e. AutoCAD)

Etak MapBase file – digital street network from Etak, Inc.

GIRAS – digital file in ASCII format containing data produced by USGS for land use/land cover maps and associated overlays for areas within the US. This includes attributes for land use and land cover, political units, hydrologic units, census and county subdivisions, federal land ownership, and state land ownership.

IGDS – Interactive Graphic Design Software interchange format for Intergraph Microstation software files, DGN design files

IGES – Initial Graphics Exchange Standard US Dept. of Commerce transfer standard

MIADS – Map Information Assembly Display grid file from the USD.A. soil conservation service

MOSS export – US Dept. of Interior's ASCII public domain GIS file format

SDTS – Spatial Data Transfer Standard, Federal Information Processing Standard 173. Federal geo-spatial data dissemination standard.

ArcView Shapefile – ESRI ArcView format file defining spatial feature(s), a dBASE file with attribute information, and an index file.

SLF – Standard Linear Format file NIMA product file of a terrain analysis product, Interim Terrain Data (ITD)

TIGER – Topologically Integrated Geographic Encoded Referencing System from USGS national map series, scale 1:100k

VPF – Vector Product Format NIMA Digital Chart of the World (DCW) information

ARINC 424 – Aviation Navigation / Airway information database with spatial component

<u>Image Formats Supported</u>

ADRG – Arc Digitized Raster Graphics – distributed on CDROM by NIMA. This data consists of raster images and other graphics generated by scanning source documents. ADRG data is geographically referenced using the equal arc-second raster chart / map (ARC) system in which the globe is divided into 18 latitudinal bands or zones. The raster data is organized by distribution rectangle; with each distribution rectangle there is one physical true color 3 band (RGB) composite image per zone.

BIL, BIP, and BSQ – an ASCII data description file that describes the layout of the image data, black and white, grayscale, pseudocolor and multiband.

DTED – Digital Terrain Elevation Data – distributed by NIMA. DTED is designed primarily for data storage and exchange. Each DTED file is arranged in 1 x 1 degree geographic areas where elevation matrix intervals vary according to latitude.

ERDAS – ERDAS Imagine format images, Rev 7.3 and 7.4 (.lan and .gis).

GRASS – Geographical Resource Analysis Support System – a public-domain GIS created by the US Army Corps of Engineers Construction Engineering Research Laboratory, Rev 4.0.

Grid – ESRI Arc / Info GRID format data - Integer and floating point grids can be used to represent discrete and continuous data, respectively. Discrete data may also be further described by continuation table information tied to the cell value attribute table.

IMAGINE – ERDAS GIS processing format. IMAGINE is a multi-band image stored together with metadata pertaining to the file in a single binary file.

JFIF – JPEG File Interchange Format images. This image format uses JPEG compression.

RLC (run-length compressed) – used for scanned monochrome images. The file is interpreted as a sequence of 16-bit words with each word corresponding to an unsigned short integer. The header is followed by the run-length compressed data for each row in the scanned image.

Sun Rasterfiles – suitable for storing monochrome, grayscale, pseudocolor, and true color images. The files have a fixed-length header that is followed by an optional variable length colormap.

TIFF – Tag Image File Format, widely used in the desktop publishing world. It serves as an interface to several scanners and graphic arts packages. TIFF supports B&W, grayscale, pseudocolor, and true color images, which may be compressed / uncompressed formats. Geographic coordinates are contained in a TIFF World file (.tfw).

GeoTIFF – TIFF World file with the geographic coordinate information stored in the header record of the file (no .tfw required). **<u>Fast becoming the industry standard for any / all GIS orthoimage formats</u>**.

LandSat – LandSat TM 30 meter Thematic Mapper satellite data EOSAT.

SPOT – SPOT Image satellite data products (many).

IRS-1C – EOSAT satellite data, 5.8 meter Panchromatic and 25 meter LISS 3 (Multispectral).

USGS DOQ – USGS Digital Ortho Quad data and quarter section scanned topos.

Formal Spatial Data Transfer Standards will continue to be developed to accommodate different data models, preserve feature relationships of even the most complex database designs, and provide a mechanism to transfer data dictionaries and metadata for certification and fitness for use.

All GIS applications software have an extensive dictionary of conversion tools to process various forms of geo-spatial data produced by vendor organizations, aviation authorities, and domestic and international governmental data providers. If an applications software package does not have a bundled converter for a specific geo-spatial data set, a platform specific decomposition tool will be developed that is compatible with the native GIS development, modeling, and viewing environment.

3.3.1.3 Terrain Data Sources

The following are the most common sources available for terrain data to date.

WORLDWIDE: SAIC terrain data. This is a digital raster file with Grid density of 30 arc-seconds (926 m pixels). The quality of this data varies depending in the part of the world it covers. The terrain was examined around selected airports and compared very favorably to both Tactical Pilotage Charts and Jeppesen NavData. The contours produced by this file are of the same quality as contours portrayed on NIMA Tactical Pilotage Charts. Jeppesen has proprietary use of the SAIC data for aviation applications. **Expanded and / or additional validation of this data set will be required for future Synthetic Vision applications**.

WORLDWIDE: NOS terrain data. This data will be released as a result of a NIMA / NOS / FAA / JEPPESEN cooperation. This is again a digital raster file with Grid density of 30 arc-seconds (926 m pixels). **This file is the exact NIMA DTED 3 arc-second data condensed to 30 arc-second for security release purposes and is referred to as DTED Level 0**. The data set currently only covers about 60% of the world. A similar data set called GLOBE is expected to have 100% coverage but won't be derived completely from DTED 3 arc-second data.

WORLDWIDE SELECTED AIRPORTS: NOS Airport Safety Model Data (ASMD). This data has 15 arc-second (463 m pixels) density on a 50 nm square-radius of an airport and 6 arc-seconds (185 m pixels) density on a 6 nm square-radius of an airport. The airport density described above applies to 450 airports (worldwide) identified by Jeppesen to the FAA in 1993 as "terrain impacted airports". Approximately 50% of those airports have been released. All US airports are available (~100), with 30% of non-US airports currently available (~100). Price: $3,500 / year.

USA: USGS 7.5 min DEM. This is a digital elevation model with a 30 m by 30 m data spacing or 1 arc-second. The DEM covers most of the contiguous United States, Hawaii and Puerto Rico. Some small gaps in the coverage exist mostly in non-mountainous areas such as parts of North and South Dakota, Nebraska, Iowa, Kansas, Oklahoma and Texas.

The 5-minute (~5 nmi) tiles use the UTM projection with NAD 27 datum and are equivalent to the USGS 1:24,000 scale maps. Elevations are provided in meters. Availability: Readily available for sale through USGS on a tape or CD (SDTS format tiles are for free download from the USGS FTP site). Jeppesen maintains a database with about 700 tiles covering approximately 160 USA mountainous airports.

USA: USGS 1 degree DEM. This is a digital elevation model with a 90 m by 90 m data spacing or 3 arc-seconds. The DEM covers all of the contiguous United States, Hawaii, Puerto Rico and most of Alaska. The 1-degree (~60 nmi) tiles are unprojected and utilize WGS 72 datum and are equivalent to 1:250,000 scale maps. Elevations are provided in meters. Availability: Readily available for download through the USGS FTP site.

ALASKA: USGS 7.5 min DEM. This is a digital elevation model with an approximate 30 m by 60 m data spacing or 1 x 2 arc-seconds. The DEM coverage is extremely limited (only 38 tiles available for the entire Alaskan Peninsula). The 7.5-minute tiles are unprojected and utilize NAD 27 or NAD 83 datum and are equivalent to the USGS 1:24,000 scale maps. Elevations are provided in meters or feet. Availability: Readily available for sale through USGS on a tape or CD.

ALASKA: USGS 15 min DEM. This is a digital elevation model with a 60 by 90-meter data spacing or 2 x 3 arc-seconds. The DEM covers a large part of Alaska. (2887 tiles available as of 8/4/98). The 15-min tiles are unprojected and utilize NAD 27 datum and are equivalent to 1:63,360 scale maps. Elevations are provided in meters or feet. Availability: Readily available for sale through USGS on a tape or CD.

Note: The USGS Data Users Guide for Digital elevation models can be obtained at: ftp://www-nmd.usgs.gov/pub/ti/DEM/demguide/dugdem.txt

The guide is comprehensive covering formats, data description, accuracy etc.

WORLDWIDE Satellite High Resolution Data: High-resolution terrain data will be needed for approximately 500 foreign airports. This data is available from a variety of vendors and pricing varies. Vendors include satellite companies (SPOT, Space Imaging, RadarSat, Spin-2 etc.), government agencies and GIS companies. The higher the resolution and coverage of DEMs, the higher the price. The price of satellite terrain data may be prohibitive enough to necessitate waiting for the Shuttle Mission data (the shuttle mission is described next).

Information on Shuttle Radar Topography Mission

Overview

The Shuttle Radar Topography Mission (SRTM) is an international project lead by the National Imagery and Mapping Agency (NIMA) and NASA whose objective is to obtain the most complete high-resolution digital topographic and image database of the Earth. Launch date is set for September 9th, 1999 using the space shuttle orbiter (manifested on STS-101) as the instrument platform. Instruments used for data capture during the 11-day mission will include Spaceborne Imaging Radar-C (SIR-C) and X-Band Synthetic Aperture Radar (X-SAR) hardware.

Data / Mapping Parameters

Digital Topographic Map - Data will be used to generate a digital topographic map of 80 percent of the earth’s land surface (between 60 degrees North and 56 degrees South latitude), with data point (GIS “mass point”) intervals at 1 arc-second of latitude / longitude (~ 30 meters). Absolute horizontal and vertical accuracy will be 20 and 16 meters, respectively (will be better near ground control points). Earth land surface coverage will comprise 95 percent of the world’s population.

Mosaicable Imagery - Data will be collected via the C-band instrument to produce a rectified, terrain-corrected radar image mosaic of the mission coverage area at 30-meter resolution.

Instruments Used for Data Capture

SRTM will build on technology used during two shuttle flights of Spaceborne Imaging Radar-C / X-Band Synthetic Aperture Radar (SIR-C / X-SAR). A key SRTM technology is radar interferometry, which compares two radar images taken at slightly different locations to obtain elevation or surface-change information. SRTM will use “single-pass” interferometry, which means that the two images will be acquired at the same time, one from the radar antennas in the payload bay, the other from the radar antennas at the end of a 60-meter mast extending from the shuttle. Combining the two images produces a single 3-D image.

An additional advantage of using radar is the ability to “see” the earth’s surface through cloud cover and in darkness.

Over the duration of the mission, the C-band radar will traverse / map the region between 60 degrees North and 56 degrees South latitude four times. The X-band radar will also provide terrain mapping but with more narrow strips, i.e., not complete coverage of the earth. However, data collected with the X-band radar can be used to correlate with the center portion of a C-band terrain strip, thus providing some cross-checking of terrain mapping performance.,

Data Formats and Products

The raw data recorded onboard the shuttle will be processed by the Jet Propulsion Laboratory (JPL) and then delivered to NIMA. After NIMA validates and processes the data, it will be archived and available for conversion. It is expected to take about eighteen months to process all the data acquired by the SRTM radar system. Products that are converted and delivered to NIMA will be in two formats, digital strip or digital mosaic.

Digital Strip Format

A digital strip represents a data "take", ranging from a 1 to 40-minute radar sweep, corresponding to a range of 400 to 18,000 km of terrain coverage per take. Strip Orthorectified Images will be subsets of this data type and be comprised of approximately 1,100 km long and 80 km wide views.

Digital Mosaic Format

Digital mosaic format is created from digital strips. Strips associated with an area of interest are stitched together into a tile structure. Tile block size will be square and set at 5 x 5 degrees of latitude and longitude per side.

Level-2 Terrain Height Data: Level-2 Terrain Height Data are the final product of SRTM data conversion. These data will be height matrices in a homogeneous earth-centered ellipsoidal coordinate system. The primary Datum used for horizontal control will be WGS-84.

Height Error Data: Height Error Data are composed of the random height error estimates. The Systematic Height Error Model will be computed from the Height Error Data and contain the verification absolute height error estimates.

The Height Error Model will contain sufficient information for obtaining the estimated total error over any portion of the globe. These Height Error Data, co-registered with Level-2 Terrain, will be useful in identifying the problem areas in processing and in providing realistic relative and absolute error estimates of the Terrain Height Data.

Conclusions

The SRTM will collect these important GIS data layers during an 11-day mission in September 1999. The mission is a partnership between NASA and NIMA, domestically. Additionally, the German and Italian space agencies are contributing an experimental high-resolution imaging radar (X-band) system. GIS analysts will use the SRTM data to generate Digital Elevation Models (DEMs). These DEMs can be combined with other data for analysis of the earth's surface, which may be able to identify the location of obstacles to surface / low level air navigation for aviation applications. The shuttle mission may not be able to discern the height of some of the smaller obstacles with sufficient accuracy due to the resolution of the radars.

References / Sources

Subject Overview WEB site: URL: http://www-radar.jpl.nasa.gov/strm/

National Imagery and Mapping Agency

Fairfax, VA

URL: http://www.nima.mil

National Aeronautics and Space Administration

Jet Propulsion Laboratory

California Institute of Technology

MS 186-113, 4800 Oak Grove Drive

Pasadena, California 91109-8099

Public Information Office (818) 354-5011

URL: http://www.jpl.nasa.gov and http://southport.jpl.nasa.gov

German Aerospace Center (DLR)

URL: http://www.dlr.de

Italian Space Agency (ASI)

URL: http://www.asi.it

3.3.1.4 Obstacle Data Sources

The following are the most common sources available for obstacle data to date.

USA: Digital Obstacle File (DOF). This is a digital file (2 floppy disks) that contains all man made obstacles shown on USA NOS sectional charts. Data covers all 50 states and parts of Canada, Mexico and some Pacific islands. Obstacle coordinates are given in WGS-84. Revisions to this file are delivered monthly or quarterly, based on customer preference. (A weekly National Flight Data Digest (paper) revision to this file is available)

USA: Digital NGS*. This is a digital file that contains all US obstruction chart obstacles. This is the most comprehensive and accurate obstacle data available for USA airports. The data is available for FTP downloads from www.ngs.noaa.gov/AERO/aero.html. Revisions to this data become available on attrition basis as new field surveys take place. Obstacle coordinates are given in NAD 83. NGS data covers approximately 900 airports in the USA. As of 8/15/98, only 275 were available in digital form. The NGS obstacle coordinates for airports that don't have a digital form, is given in NAD 27.

USA: 56 day NOS revision tape*. This is a 9-track tape (also available on CD) revising the FAA form 5010 as well as the Airport Facility Directory (AFD). Of interest are the 5010 obstacle field updates. Revisions to the tape come every 56 days. The quality of the data is somewhat questionable. Only one obstacle is listed for every runway end. This obstacle is considered to be the "critical" obstacle. Some obstacle information is also listed in the notes field of the data. This data can be used for airports that don't have an NGS survey, usually smaller and VFR airports.

USA/INTL: DOD Air Force Form 3628 Data Verification*. This is a paper list of obstacles around military air bases. The list covers worldwide USA controlled air bases. The lists are available to Jeppesen in support of airlines supporting military related contracts. Revisions will be available on demand from the Air Force.

INTL: NIMA DVOF file. This is a 9-track tape of worldwide man made only obstacles. Jeppesen obtained this file as part of the Air Force One contract. It can also be used to support airlines supporting military related contracts. Due to liability issues, NIMA has not yet allowed Jeppesen to use this file for full production. The minimum obstacle height reported in the file varies. On areas surrounding airfields or over water the heights go as low as <50' AGL. Revisions to this file come on a monthly basis.

INTL: Foreign Government Agencies & Aviation Information Publications (AIPs).* A multitude of obstacle sources are here. Some countries carry very detailed listings others don't. The vast majority of these sources come in paper form. To extract the obstacle data, a minimum of 1,000 Obstacle charts and multiple other graphic AIP charts need to be manually digitized. Accuracy of the data is unknown. Revisions to AIPs vary and are unpredictable.

*Note: These sources may contain some natural high points as obstacles, i.e. terrain shown as high points.

3.3.1.5 Airport Data Sources

There are many spatial data sources for constructing an accurate airport map. The map must be comprehensive enough to support the operation / tracking of aircraft and vehicles in the airspace envelope as well as other remote user sites. The cartographer must draw from many potential spatial data sources ranging from paper maps to geo-rectified high-resolution aerial or satellite orthoimagery.

The developer must also compile descriptive tabular information about the spatial features represented in the airport GIS. Descriptive information and / or metadata may be gathered via conversion of existing digital tabular information, client interviews, field work, programmatic conversion of CAD layer/level feature classifications, and other creative techniques.

All these potential data sources should be considered prior to constructing an airport GIS. One source may be adequate or a combination of many may be valid depending on the accuracy and feature specificity of the intended application.

To date Jeppesen has developed detailed and highly accurate mappings of the Atlanta Hartsfield International Airport and the Denver International Airport. The approximate size of the Atlanta airport database, containing extensive thematic layers of information to ~1 meter accuracy is ~3.7 giga-byte. The Atlanta airport database was developed to support an industry demonstration of Low-Visibility Landing and Surface Operations (LVLASO) by NASA and FAA in the fall of 1997.

3.3.1.6 Navigational Data Sources

Navigational data is available from Jeppesen NavData. This is a worldwide source providing a comprehensive set of aeronautical data used by many airlines to date associated with Flight Management Systems. Due to the extensive use of this data by the aeronautical industry, issues are not expected. This data set is currently used by Flight Management Systems to navigate a plane from take-off to landing and has proven itself over time.

3.3.1.7 Cultural Data Sources

Cultural data will include roads, rivers and other identifying geographical features. Based on the resolution required, some data may be retrieved from the Digital Charts of the World (DCW), currently known as V-Map Level 0, or other government data sets. This is a worldwide source of electronic data originally derived from Operational Navigational Charts (ONC).

Since the V-Map Level 0 cannot support the accuracy required around airports, more detailed data will have to be defined from local airport / aerial surveys (see Section 3.3.1.5 on Airport Data Sources).

3.3.2 Database Issues

The purpose of this section is to identify issues associated with data, process and integration. The subsequent section will provide some means for mitigating these issues (Section 3.3.3).

3.3.2.1 Cost and Acquisition of Data

Data is required to define terrain, obstacles, and airports. This section will discuss the issues associated with acquiring sufficient data to satisfy the application needs.

Terrain Data

In order to satisfy the data requirements for the SVS applications identified in Section 2, several levels of accuracies and resolutions need to be considered. Table 3-1 summarizes the terrain database requirements as a function of flight phase and provides a diagram displaying concentric circles demonstrating these phases of flight. For the enroute phase of flight, 100-meter accuracy with 150 arc-second (2.5 nmi) or 30 arc-second resolution is required (refer to discussion on enroute terrain database requirements in Section 2.6.5).

Enroute terrain data to 300 arc-seconds is readily available through SAIC and should be globally available from NIMA as well during 1998. Both sources actually provide a 30 arc-second resolution data set that is also applicable for the departure / approach phase. The required 150 arc-second terrain data is not readily available at this time but may be derived from available 30 arc-second data from both SAIC and NIMA.

For higher resolution data sets at mountainous airports and for the takeoff / landing phase, data is not as readily available outside the United States. NOS has released the first version of the Airport Safety Model Data (ASMD) that provides resolution to 6 arc-seconds around mountainous airports.

This data however is only accurate to within ±30 meters and only covers approximately 50% of the required airports. To satisfy mountainous airports at 15 arc-seconds for departure / approach phase that the ASMD does not cover, Jeppesen has contracted with SAIC to produce this data from available cartographic source at approximately $1,000 per airport.

The expected accuracy for this data however is only at about ±50 meters and may not satisfy the application requirements. Accuracies better than ±30 meters needs to be obtained from satellite imagery.

The most common source at this time is from Spot Image. For areas that clouds have not obscured, Spot can provide highly accurate and resolute digital terrain data at ±10 meters vertical accuracy.

The cost however is about $10,000 per scene, with a scene covering about a 37 x 37 square kilometer area. This area should be sufficient to satisfy the takeoff / landing phase but is considered cost prohibitive for an extensive number of airports. Note: Current satellite techniques are not effective where extensive cloud cover is prevalent. New Synthetic Aperture Radar satellites however should help to resolve this issue.

For the Airport surface data, the only means to satisfy 1-meter accuracy is from local aerial photogrammetry. Approximate costs per airport are about $30,000 per airport. Although very costly, the accuracy and resolution are more than sufficient for the applications proposed for Airport surface operations. However, this is quite cost prohibitive for an extensive number of airports.

In summary, global terrain data to satisfy the enroute phase of flight (150 arc-second gird) can be easily derived from existing 30 arc-second data. 300 arc-second data is already available if adequate for enroute operations.. For the United States, data to satisfy the departure / approach phase of flights is readily available, with partial availability globally. The only restriction is about 250 foreign airports within mountainous regions that require higher resolution data. For the takeoff / landing phase, data at 10-meter accuracy is not readily available and would cost about $10,000 per airport to generate this data using current satellite images.

Obstacle Data

For the obstacles listed previously, the following are the costs and availability of this data.

USA: DOF file: Yearly Subscription from NOS: $107

USA: Digital NGS: Free on the Net

USA: 56 day NOS revision tape: ~$200 / year for the obstacle tape / CD.

USA/INTL: DOD Air force Form 3628 Data Verification: Cost Unknown. This source is provided very sparingly and only for airlines supporting military related contracts.

INTL: NIMA Digital Vertical Obstruction File (DVOF): Cost Unknown. Although this is a comprehensive (worldwide) source for obstacles, it is NOT currently available for commercial use.

INTL: Foreign Government Agencies & Aviation Information Publication (AIPs): The cost of AIP subscriptions vary substantially from country to country. A large-scale effort will be necessary to capture this data. Even though AIPs represent official government data, its accuracy is questionable for many states. A recent survey revealed that most governments lack a reliable system to monitor obstacles.

If the NGS accuracy standard is used to survey obstacles at airports worldwide, it will be a very costly and long-term undertaking. Currently, availability of obstacle data to this standard is severely lacking. To be able to support SVS applications, enhanced development of a worldwide obstacle database is absolutely required, and an effort through international standards organizations such as ICAO must be undertaken.

For all practical purposes it can be assumed that data for many parts of the world cannot be obtained even through these organizations. Therefore, the only alternative means of obtaining data for these places will be satellite imagery or aerial photography.

Airport Data

Future Synthetic Vision applications may require highly accurate airport data to support airport surface operations. Current availability for this data at the accuracies required, however, is very limited and has only been generated for a few sample airports worldwide (Atlanta, Denver). As stated previously in the data sources section (Section 3.3.1), current technologies require the use of local aerial photogrammetry that can survey the airports within the 1-meter accuracy as required. The current cost per airport is very costly at about $30,000 per airport.

This is a time consuming and expensive endeavor and it will take many years to produce an extensive set of airports in order to satisfy requirements. However, in order to support the future SVS applications, processes and infrastructure to generate and manage this data must be developed.

3.3.2.2 Database Integrity / Validation of Data

Database Integrity

SVS database integrity is a primary issue for the development of future SVS applications. As summarized in Section 2.6 (Table 2-4) candidate SVS applications fall into the categories of 1) safety systems, 2) strategic, and 3) tactical. Overall system integrity generally increases for each of these categories, from ~10^{-3} to 10^{-5} for safety system applications to ~10^{-5} to 10^{-9} for strategic systems, and better than 10^{-9} for tactical systems (refer to Figure 2-2 for effects categories related to integrity). It was also noted in Section 2.6.3, that the SVS database(s) directly impacts the integrity of the SVS application. The SVS source data either has high data integrity or it does not. The SVS application itself cannot perform any monitoring function to determine the state of data integrity. Thus, the integrity of SVS databases plays a crucial role in being able to certify high-criticality SVS applications.

System integrity is often specified in terms of "probability of undetected failure rate" over some interval of time or operational flight phase. A low probability of undetected failure indicates high system integrity. In typical avionics system, techniques to boost system integrity are as follows:

- First, the system must have a high probability of providing the specified level of performance when the system is working properly.
- The system must have a low probability of failure, i.e., high mean-time-between-failure (MTBF).
- Addition of monitoring and built-in-test equipment (BITE) functions allow detection of system failures. The effect of monitoring / BITE is to lower the probability of undetected failure, i.e., boost integrity.
- Using system redundancy, perhaps even using dissimilar implementations, further increases system integrity. Redundancy allows comparison of system outputs and allows detection of system failure. Use of dissimilar implementations ensures that one implementation does not have a systemic flaw that could adversely affect integrity.

The above discussion is from the perspective of how an avionics system achieves integrity. For integrity of SVS databases, the source data provider may have to use similar techniques to ensure that the database information provided is correct to a certain integrity level.

The following example attempts to illustrate how SVS integrity may be viewed. For example, assume a worldwide terrain database with a 30 arc-second elevation grid / post spacing and 10^{-7} integrity:

1) Database integrity may be viewed as the number of undetected elevation post errors relative to the actual terrain. The entire earth's surface contains approximately ~600 million elevation posts for a 30 arc-second grid spacing. For 10^{-7} integrity (i.e., probability of misleading information), if less than 60 elevation posts are in error beyond some error margin, then the database may be viewed to meet the integrity requirement.

Note 1: Error margin consists of horizontal and vertical containment buffers that include data accuracy and may also include additional safety buffers to ensure worst case allowable terrain deviations. It should be noted that from this perspective, data accuracy, e.g., +/-10 meters, does not represent integrity. However, integrity indicates the rate at which the elevation posts (with associated accuracy) are correct relative to the actual terrain. Thus, it is possible to have a low accuracy database with very high integrity, and conversely a high accuracy database, that has many undetected errors or low integrity.

Note 2: Integrity can also be boosted by increasing the safety buffers associated with terrain. As an extreme example, by placing the terrain safety buffer at 30,000 ft, one can safely determine that no terrain errors can impact SVS operations since this exceeds the elevation of Mt. Everest (29,028 ft elevation).

2) Database integrity could also be computed over the extent of the terrain database that is encountered during a particular phase of flight, e.g.,enroute, where only a fraction of the earth's surface is traversed. For example, a 5000 nmi flight with a 500 nmi corridor of terrain represents ~1.7 % of the entire earth's terrain (i.e., 10 million elevation posts). For 10^{-7} integrity over that duration of flight, only 1 elevation post may be in error.

In order to achieve high-integrity SVS databases (e.g., terrain databases) data providers may need to do the following:

1) Determine the ability of their terrain data gathering process to achieve elevation data within a specific, acceptable error / accuracy tolerance.
2) Determine the probability of failures in the data collection process.
3) Use monitoring equipment to determine when the data collection process has failed, and go back and recollect data when error is repaired.
4) Use redundant data collection from independent sources. Data collection process could use same technology or could use dissimilar process to avoid the chance for undetected systemic errors in the data.

Clearly, these are critical and important steps in developing high-integrity databases that will be difficult and costly to achieve. Data validation is required among data sets to detect errors and then correct them to boost integrity. The fundamental problem is knowing what data is "truth". The next section discusses validation of data that lead to higher-integrity databases.

Validation of Data

Validation has been defined as ensuring that the data satisfies the needs of the intended application. In order to ensure this intent, accuracies have been defined for the required data sets, but the question is, how does the manufacturer ensure that the data satisfies the intended requirement?

It is expected that from a liability and certification concern, a sufficient means to validate Terrain, Obstacle and Airport data will be required. The biggest question concerns how is the data validated and what is the "truth" that can be used to validate against?

Data is typically provided with a published accuracy. It is not expected however that this alone will satisfy the certifying authorities for the expected applications within the departure / approach and takeoff / landing phases of flight.

Data can be validated by cross checking against other sources. Cross checking against multiple sources, assuming that these sources were derived from different means, can help to ensure the viability of the data. Cross checking with known "truth" data can also be performed. Truth data sets however may be hard to come by.

It has been suggested that for aeronautical purposes, data associated with established IFR procedures and runways should be utilized to ensure that minimum clearances can be obtained using the terrain and obstacle data sets.

This data has been flight tested using current Flight Management Systems and is very carefully scrutinized to ensure that safety of flight is not compromised. The readers should note, however, that this will only validate the terrain data along established flight paths and will only ensure that the terrain data is not too high to induce false warnings. It does not check that the terrain data is too low and therefore not produce warnings when it should.

The ultimate form of validation is to flight test the data, ensuring that warnings are not produced or are produced as expected. The expense of this however from both a cost and time standpoint however could be prohibitive.

In summary, validation of the data to ensure that the data will satisfy the intended requirements could be limited due to insufficient "truth" data to validate against. The only current truth data reliable enough to use will satisfy IFR airports only. For VFR airports, it is uncertain at this time what "truth" data can be used to ensure that the data will satisfy the application needs.

3.3.2.3 Integration of Different Data Elements

Terrain and Obstacles are required data elements for the intended SVS applications. Since these data sets must be used in concert with one another, it is imperative to ensure that when integrated, they do not contradict one another.

In other words, an obstacle should not sit well below or above the terrain model. This issue is tightly coupled with validation. It is expected that in order to effectively integrate terrain and obstacles databases, they will have to be validated against one another.

The biggest issue with this will be when obstacles do not integrate well with terrain, determining who's right and who's wrong could require some effort. Obstacles have varying degrees of accuracies and are sometimes verified and sometimes not, therefore resolving the discrepancy will become the issue.

Another issue associated with integrating different data elements is dealing with different datums. This is discussed in more detail in the Section 3.3.2.11 on data conversion between different systems.

3.3.2.4 Resolution of Discrepancies

The previous two sections discussed issues associated with validating data to ensure that it is suitable for the intended use. This validation can occur with a standalone data set or in relation to other data sets. A major issue derived from the validation is if a data set is not accepted, i.e., it does not pass the validation test, how is the data resolved such that it can be effectively used.

When dealing with data from government agencies, it is not expected that originating agency will "fix" the data. Therefore, the distributor of the data must resolve any discrepancies, or must contract with somebody to resolve the discrepancies.

Current validation techniques compare navigation data at runway ends and defined instrument approach procedures with terrain and obstacle data. This isolates the current validation to the approach / departure and takeoff / landing phases of flight. Based on these validations, the discrepancies discovered will be associated within about 30 nmi of the airport. These are areas that require a higher level-of-detail for both terrain and obstacle data based on the requirements of the SVS applications.

Discrepancies can typically be resolved by integrating higher resolution cartographic sources to supplement the existing sources. SAIC is a private firm that, provided sufficient source data is available, will reproduce their data set at a cost of about $1,000 per airport. If sufficient cartographic source data is not available, then acquiring source data from Satellite imagery would be required. <u>It is possible that reliable satellite or cartographic sources are not available and that use of SVS applications for that airport would have to be restricted</u>.

Data producers will also be required to adhere to a strict set of standards associated with the management of the data sources and the resolution of discrepancies. This will typically involve a very well defined set of procedures that will outline how a discrepancy is resolved, and how the corrected source data is effectively integrated with the existing sources. This is basically known as Configuration Management, and will be required by any certification authorities. <u>Data producers will be required to have Quality Control procedures in place and will have to prove that they have adhered to those processes</u>.

3.3.2.5 Updates to Data, Data Load Strategies

<u>Temporal Database Factors – Database Update Strategies</u>

When geo-spatial data is first acquired or captured, it must be current as of that point in time. It should accurately represent features or themes pertinent to the user's needs. The accuracy level of the data is also dependent on the strategic, tactical, or analytical use of the information.

A temporal component should be included in the design of the data dictionary. Each spatial feature should be attributed with the date / time value equating to the time it was generated, using methods such as: digitizing, digital orthoimagery, and field mapping.

At such time that there is a change to the geographic surface or attributes describing it, whether caused by human intervention (buildings / structures or other construction activities) or nature (geologic, hydrologic, or vegetation cover), and it effects information critical to support a certain phase of flight associated with an SVS application, then it must be incorporated into the geo-spatial / geo-referenced database. Update strategies could employ several techniques, including:

- Setting up a network of information providers, vendors, airports, regional or local / municipal government agencies, aviation industry sources, etc. to relay change information based on a set of business rules or criteria that effect the flight information database.
- Establish a temporal data refresh schedule and capture digital orthoimagery and / or surface vector / raster geospatial information and use the power of the GIS to perform overlay, intersect, and other change detection operations on new versus old data sets.

New data is appended to the current data set, while data that involves changes requires replacement operations.

Historical information should be saved and archived for later modeling or comparative analysis. All transactions should be recorded in an audit buffer so the user can recreate a historical condition, should the need arise.

Data Transfer and Data Load Strategies / Standards

It is important to develop data transfer and update standards between the graphics format employed by the GIS applications development team and the organization that is responsible for loading the map and tabular data into the display system. The conversion and update process should be kept to a minimum and database compatibility should be maximized, if possible. Common graphics data exchange formats are shown in Table 3-3.

SPATIAL DATA EXCHANGE FILE FORMATS
Arc/Info (ESRI) Coverage Export File
Shape File Format (ESRI ArcView binary)
DXF – Data Exchange File Format (universal)
DGN – Intergraph Design File Format
DWG – AutoCAD Draw File Format
SDTS – Spatial Data Transfer Standard

Table 3-3 Common Spatial Data Exchange File Formats

Optimally, the developers of the data and developers of SVS applications should strive to share spatial information via one of the above file formats.

There will be a need to share, transfer, and update tabular database information as well as graphics. Some formal spatial / tabular data transfer and update standards must be developed to accommodate different data models, preserve feature relationships of even the most complex database designs, and provide a mechanism to transfer data dictionaries and metadata / continuation tables for certification and fitness for use.

The data must be coded with a “temporal” component or attribute. This temporal attribute should drive any update and / or data replacement process that is instituted. When attribute or spatial features change, data occupying that geographic area will be updated/replaced with data tagged with a more recent date/time component. Older data should be archived for future reference, or for purposes of historical analysis or change detection.

GIS and RDBMS (Relational DataBase Management System) applications software have an extensive dictionary of conversion tools to process various forms of geo-spatial data produced by vendor organizations, aviation authorities, and domestic and international governmental data providers. If an applications software package does not have a bundled converter for a specific geo-spatial data set, a platform specific decomposition - conversion and / or update tool should be developed that is compatible with the native GIS development, modeling, and viewing environment.

Computer links and / or networking to onboard or ground based server systems could be established in a couple of ways. Linking could be done via direct cabling of components or use radio communications methods, i.e., datalink. Among potential aeronautical datalinks are gatelink, wireless local area network (LAN) at airports, or other data links such as VHF datalink, satellite communications, etc.

3.3.2.6 Storage and Compression of Data

Database Architecture and Filesystems

It is anticipated that the geo-spatial / geo-referenced data needed to support SVS applications through all phases of flight will be very large, requiring significant amount of data storage. Each phase of flight will require a unique subset of information extracted from a specific level of the database file system. This data will be viewed at various levels-of-detail (LOD) and will be integrated with a range of data types (terrain, obstacles, cultural features, airport data, navigation data, aircraft state and guidance information, etc.). It is important to fully normalize and tune the database architecture and file-system structure to maximize transaction-processing speed. This is particularly true for the demanding SVS information processing tasks and subsequent graphics rendering of SVS display data to satisfy the display frame rate requirement (typically 30 Hz).

Table 3-4 provides an estimate of the size of data for various SVS databases.

Type of Data	Local Data Size	Worldwide Data Size
Worldwide Terrain Data (30 arc-second gird)	-	~1.2 Gbytes
Airport Terrain Data - 15 arc-second grid - 100 nmi square	~320 Kbytes per airport	~1.6 Gbytes (5000 airports)
Airport Terrain Data - 6 arc-second grid - 12 nmi square	~28.8 Kbytes per airport	~140 Mbytes (5000 airports)
Airport Terrain Data – 1 meter grid – 5 nmi square	~170 Mbytes per airport	~850 Mbytes (5000 airports)
Atlanta Hartsfield GIS Database	~4 Gbytes	-
Worldwide Airport / Navigation Aid Database	-	~10 Mbytes
Worldwide Obstacle Data	-	~250 Mbytes
Worldwide Raster Image – Less than 2 meter resolution	-	~13 Terabytes (compressed) ~55 Terabytes (uncompressed)

Table 3-4 Estimate of Data Storage Size of Various SVS Databases

As seen in Table 3-4, data storage requirements can be extensive and pose a significant challenge for potential SVS applications. Compression techniques can reduce the storage burden to some extent. The compression algorithm must provide for lossless and fast compression / decompression of data to accommodate the SVS real-time system. Candidate compression algorithms are PKZIP, GZIP, Mister Sid, and algorithms using Huffman or vector quantization coding.

Since the SVS database storage requirement is extremely large, a tradeoff must be made as to what data should be loaded on an aircraft. Whether an aircraft stores an entire worldwide SVS database, a regional SVS database, or only the portion of the SVS database needed to conduct the upcoming flight can be traded-off depending on the availability, cost and downloading time associated with data storage and database update / data loading capability.

Current state-of-the-art Fast Flash Disk (FFD) storage technology provides storage capacity in excess of 4 GBytes with an access time of < 100 microseconds, sustained read / write rate of 2.8 / 2.0 Mbytes / sec, burst read / write of 10 Mbytes / sec, and excellent reliability. In addition, the FFD technology can incorporate the use of embedded error detecting and correcting hardware / coding (e.g., using a Reed Solomon code). This can be used to insure that the integrity of the stored data is maintained and that errors are not introduced that could result in the use / display of misleading SVS information.

Raster Data Compression

Raster-based data sets will be utilized to support the synthetic vision system. These georectified images will be contained in the form of digital orthoimagery (i.e. aerial orthophotography); satellite gray scale, color and multi-spectral imagery; digital elevation or terrain model grids; and other grid / raster / cell based geospatial products.

Any raster / grid data compression engine should have certain characteristics that will aid in the display of this form of geospatial information.

It will be important to quickly display / view gray scale and color imagery, 3-D hillshade views, and 3-D perspective views with imagery draped over a digital terrain model. These are just a few of the rapid-view "scenes" that may be required in a fully deployed synthetic vision system (SVS).

Section 3-4 further examines issues associated with the SVS database architecture and display generation / rendering of SVS data on cockpit displays.

Image Data Compression Criteria

Some of the criteria that must be met by an image GIS data compression engine include:

- View huge images fast
- Superior image quality (no degradation of pixel resolution at any compression level)
- Multi-resolution (generate 1X, 2X ,3X ,etc. resolution levels on the fly)
- Seamless browsing, no tile or mosaic structure
- Selective decompression, based on view / scene map extent
- High compression ratios

The project should also consider the use of or address available WEB image server utilities. It is expected that the internet could be used effectively to support the distribution and update of images.

The following is a list of the minimum number of raster / image / grid file formats that should be supported by the data system (definitions for these formats are discussed in section 3.3.1.2):

- TIFF
- GeoTIFF
- BIL
- BIP
- USGS DOQ

As noted previously, GeoTIFF uses a TIFF world file (.twf) with the geographic coordinate information stored in the header record of the file, and is fast becoming the industry standard for any / all GIS orthoimage formats. Larger imagery data can be pieced together in the form of GeoTIFF tiles, where each GeoTIFF tile is compressed individually to minimize storage. When an SVS application needs to access a portion of the SVS database, it only needs to access the appropriate GeoTIFF tile (as indicated by the geographic coordinate information in the header) and decompresses the individual tile. This can be accomplished much faster than decompressing the entire imagery data file. This is one way to achieve the speed necessary to enable the SVS application processing system and graphics rendering to be done in real-time.

3.3.2.7 Ownership of Data

Terrain, obstacle and airport data are all expected to come from different sources. They may also come from multiple sources. Each agency individually owns their data and is responsible for the proper distribution of that data.

With various data elements required from expected multiple sources, having an organization to compile these sources to ensure that timely and proper updates are applied becomes an integral part of the process.

3.3.2.8 Certification of Data and Data System

Several layers of certification are expected with Synthetic Vision applications. Although the data is not specifically certified, DO-200A provides the guidelines by which the process that produces, maintains, distributes and integrates the data is certified. Some of the key features associated with this process certification are configuration management, verification and validation. Any manufacturer of data will need to be certified to DO-200A standards.

Note that although data is NOT certified to date, it is expected that certifying authorities will require a higher level of integrity for strategic and tactical SVS applications such that data certification may have to be considered.

The second level of certification is expected to be provided by the vendor that integrates the data with the SVS application. In order to prove the system, the data must also be proven to some extent as well. As stated previously, the ultimate form of validation is to flight-test the data with the system. It is likely that manufacturers will be required to include the database testing during the flight test of their systems.

Depending on the application, the extent of this certification will most likely progress from SVS safety system applications to strategic and tactical SVS applications. For tactical applications, extensive certification is expected at all airport locations, while for safety system and strategic applications, effective use of the system may only need to be demonstrated for selected areas.

3.3.2.9 Liability

Although it is expected that with the anticipated validation and certification requirements the likelihood of a libelous situation occurring is greatly reduced, it cannot be assumed that it is unlikely and therefore must be considered.

Currently government agencies distribute their data without assuming any liability. This must be addressed for future applications requiring more accurate data. Governments must be willing to stand behind their data. Data distributors such as Jeppesen currently assume a certain level of liability for the data based on the premise that they will accurately reproduce data as provided from government source.

Avionics manufacturers also must assume a certain level of liability based on their applications fulfilling the intended requirements. For tactical applications that will actually navigate the plane, this liability could be extensive due to the ramifications of a mishap occurring based on a system or database error. For SVS safety system applications liability is expected to be reduced since situational awareness the primary intent, not aircraft guidance.

A concern however has been raised for situational awareness applications that, depending on the display, a pilot may still use this display to navigate. This would use the application in a way that is neither certified nor recommended, but these disclaimers may not be adequate to indemnify the avionics manufacturer against damages. Section 5 takes a more detailed look at SVS certification and liability.

3.3.2.10 Processing of Multiple Sources of Data

A single source that will satisfy enroute applications is available, but even that single source most likely used multiple sources to produce a single model. SAIC uses approximately 45 different sources and fuses these data sources into a single model using a multi-variate Kriging methodology. While SAIC has determined that this process produces the most effective model, not all data producers use this method.

When integrating multiple sources, each source must be individually evaluated and weighted such that a more accurate and resolute source will have more influence on the fused data model. This weighting of data sources can be a subjective decision open to debate. To what extent this entire data integration process must be certified and proved is of question.

Since it is expected that multiple sources will be used to generate a single data model for terrain, configuration management of those data sources becomes an issue. Configuration management deals with cataloging data sources and documenting the production process such that terrain models can be accurately reproduced. As discussed previously under certification, appropriate configuration management is essential for gaining approval of the process used to create the data.

3.3.2.11 Data Conversion Between Different Systems

We have discussed how different data sets for terrain, obstacles and airport data are required for the SVS applications. It is highly likely that data from multiple sources were produced using different datums, some that maybe produced from local datums that are not well known.

The integrated data sets, however, will require a common datum, typically WGS-84. While datum conversion routines are available from NIMA, they may not cover all source datums.

It is possible that a given source may not have a defined datum and one may need to make an educated guess on the datum that was used. If features from this data source cannot be matched up with other sources of known datum, then the data source with the unknown datum will have to be rejected.

The issue and risk therefore is that not only must the terrain, obstacle and airport data conform to a common datum, but that other aeronautical instruments / navigation systems, which provide data inputs to the SVS applications must be converted to the appropriate datum.

For safety applications, this datum shift may not be significant enough to produce a dramatic change, but for tactical applications, based on the accuracies required, this is a significant issue. For example lateral errors of 1,100 ft can occur in Japan when using the Tokyo datum relative to WGS-84; also 100 m vertical errors may occur if vertical datum issues are ignored. Appendix B provides an overview of geodesy and datum issues pertaining to SVS that further discuss the datum problem.

3.3.2.12 Verification

Verification is different than validation in that verification deals with ensuring that no inadvertent errors are introduced into the system. This is essential for DO-200A certification and should be present for the entire life cycle of the data. More than likely it will be required for the data as it exists within the application as well. A continual form of verification will ensure that no errors are introduced while the data is on-board the aircraft. This will be an integral part of any application, regardless of phase of flight.

3.3.3 Mitigation of Database Issues that Concern SVS Applications

The previous section (Section 3.3.2) identified issues associated with data, process, and integration. The intent of this section is to discuss how these issues could be mitigated, if possible. Those issues that cannot be mitigated will be designated as major issues that could prevent implementation.

3.3.3.1 Cost and Acquisition of Data.

This issue deals with whether or not data exists to support the SVS applications and examines the cost that may be required to obtain the data. The discussions will be separated into the three major data types, terrain, obstacles and airport data.

Terrain Data

In summary, terrain data exists to support applications requiring 30 arc-second resolution or less resolute data. This will satisfy SVS safety system applications except where higher resolution data is required in mountainous areas. For these areas within the United States, either the ASMD data will satisfy the requirements, or data sets can be derived from USGS DEMs.

The real issue concerns terrain data for outside the US. Currently about 100 airports are supported by ASMD outside the US, but that leaves about 250 foreign airports that still require higher resolution data. Using SAIC as an independent source to develop higher resolution data for these airports will cost an estimated $250,000 dollars. It is estimate that this data could be completed within a year. This expense could be further mitigated if NIMA and / or governments in Europe could be convinced to allow the ASMD data set to be expanded in their region. Currently most of the western European countries have withheld authority that would allow NIMA to release ASMD data through NOS.

Data whose accuracy approaches 10 meters is required for the takeoff / landing phase of flight can currently be obtained reasonably by using satellite or aerial imagery.

Current cost is estimated at about $10,000 per airport assuming that a 37 x 37 kilometer area is sufficient area around the airport. Cost could go up if a larger area is required. Assuming that this level of accuracy is required for only mountainous airports totaling about 450 (refer to Section 3.3.1.3), the costs would be about $4.5 million.

More than likely if this level of accuracy is required, it would be necessary to support at least all worldwide IFR airports that currently totals about 5,000 airports. The total cost would be about $50 million dollars. This cost may be mitigated by improved data from the Shuttle Mission or other new commercial technologies.

The Shuttle Mission is expected to fly in 1999 and will require at least eighteen months to process the data. The data derived from this mission is expected to provide at worst 16-meter vertical accuracy and at best 8-meter accuracy. Since some ground control data is available for most airports, it can be expected that the data should support closer to the 8-meter accuracy figure for around airports.

The Shuttle Mission and additional commercial satellites should also help to reduce the existing costs of higher resolution and more accurate data. Satellite companies will more than likely be reducing the costs of their data trying to get return from their data prior to the release of Shuttle data because the Shuttle data is expected to be provided at a minimal cost. Note that even the Shuttle will not cover the whole world but it is expected to include a very high percentage of the airports required.

Obstacle Data

The issue with Obstacle data resides mainly outside the US. As discussed previously, if the NGS accuracy standard is used to survey obstacles at airports worldwide, it will be a very costly and long-term undertaking. Currently, availability of obstacle data to this standard is severely lacking. To be able to support SVS applications, enhanced development of a worldwide obstacle database is absolutely required, and an effort through international standards organizations such as ICAO must be undertaken.

For all practical purposes it can be assumed that data for many parts of the world cannot be obtained even through these organizations. Therefore, the only alternative means of obtaining obstacle data for these places will be via satellite imagery or aerial photography.

Unlike for terrain data, the Shuttle Mission goals do not include generating obstacle data. Current discussions revealed that the data produced from the Shuttle Mission will include a “vegetation bias” that will be a part of the data. Buildings could be included with this bias. Smaller obstacles such as towers however will not be evident enough to be derived from the shuttle or other satellite imagery.

Airport Data

SVS surface movement applications require the most accurate airport data. Discussions of surface movement airport databases are not emphasized in this study. The main issue is cost and timeliness to support the resolution and accuracies required. It is not expected that Shuttle Data will provide the accuracy required.

The alternative is the current method using resolute aerial photography or the use of new satellites that will provide sub-meter accuracy. The current cost is about $30,000 per airport for aerial photography, by contrast the cost is unknown but is expected to be less for satellite imagery. This is still expected to be a costly endeavor, and the time required to complete a significant number of airports could also be prohibitive.

3.3.3.2 Validation of Data

Validation is an issue since it is expected that certifying authorities will require avionics manufacturers to ensure that the data is suitable for the intended use. It is not expected that any current source will be accepted as is without some form of validation, nor is it expected that any future sources will automatically qualify as well.

The data from the Shuttle Mission may prove this statement wrong, but at this point it is anticipated that even the Shuttle Mission data will have to be validated like any other data set. The issue then becomes what is extent of validation required to ensure that SVS databases have adequate integrity, and what will the cost be for such validation efforts. Current validation processes use IFR runway and approach procedure data that is used currently by FMS systems, since the FMS is proven and considered highly accurate.

This validation process can be automated and once the system is built, the cost of automated validation is expected to be reduced considerably. Current validation is only for the 5,000 IFR airports and does not include VFR airports. It is not clear at this time what would be used to validate these additional airports. If the shuttle data validates successfully for IFR airports, it is uncertain whether the certifying authorities will accept that the data would also validate appropriately at VFR airports.

Time may be the biggest factor for mitigating validation cost. As the available data is used and becomes proven, a higher level of confidence will be obtained that could eventually lower the validation requirements. However, since the validation process can be automated, it will probably continue to be used.

<u>The issue will therefore become what will be used as “truth data” to expand the existing processes. It is not clear at this time what that “truth” data will be.</u>

3.3.3.3 Integration of Different Data Elements

Integration of different data elements is an issue especially when the data is derived from different sources and it is unclear which data set is more right than the other. The simplest way to mitigate this issue is to derive the different data elements from the same source. This will ensure that the data can be seamlessly integrated but assumes that this single source is highly reliable and will provide the accuracy as required. It is possible that the Shuttle Mission can provide this single source in the future.

If a single reliable source is not available and there’s a difference noted when trying to integrate multiple data sources, the issue becomes who’s right and who’s wrong. If another source is not available to resolve the issue, then to be safe the higher elevation of the two data elements could be used.

3.3.3.4 Resolution of Discrepancies

Based on tests performed with existing data from SAIC and NIMA, it is evident that there will be some areas that do not pass the current acceptance criteria. The number of airport areas that do not pass acceptance at the current vertical 100-meter value for 30 arc-second data is about 100 airports out of about 5,000.

The cost to resolve these discrepancies is expected to be about $100,000. SAIC will support 50 meter vertical accuracy for 15 arc-second data but at this time, that will not satisfy the 30 meter accuracy currently required for the approach / departure phase. Note that 75% of the airports identified with 30 arc-second data have discrepancies of less than 20 meters.

Although SAIC cannot guarantee that data can be produced that will satisfy 100-meter or 50-meter accuracy, the data can be designated according to how well it does compare. Synthetic vision applications would then be required to indicate they cannot be used because there is insufficient data / accuracy to perform the intended function. If SAIC cannot acquire sufficient source data to resolve discrepancies, then Satellite imagery, if available, would have to be used.

For government data that does not pass acceptance, it is not expected that they will be able to resolve the discrepancies using the current data set. The only mitigation for data from NIMA is the promise of accurate data from the Shuttle Mission.

The Shuttle Mission could potentially be a panacea for all discrepancies if the expected accuracy is proven. If the Shuttle Mission data does not provide the raw data that can be subsequently integrated with commercial obstacle and cultural feature data, then more traditional surveying and data gathering will be needed.

3.3.3.5 Updates to Data, Data Load Strategies

Temporal Database Factors – Database Update Strategies

The main issue with data updates is the timeliness by which the data is updated. Since the avionics is an automated system, a NOTAMS type of update will not suffice. A timely automated means to update data such that flight safety is not compromised needs to be considered. Since terrain data does not change very often, automated update is more important when dealing with obstacle data, which are more likely to change. Terrain may be reloaded / updated in the avionics system when a new, improved terrain data source becomes available. Otherwise terrain data is not expected to change much. The following provides some possible solutions for database updates.

- Setting up a network of information providers, vendors, airports, regional or local / municipal government agencies, aviation industry sources, etc. to relay change information based on a set of business rules or criteria that effect the flight information database.
- Establish a temporal data refresh schedule and capture digital orthoimagery and / or surface vector / raster geospatial information and use the power of the GIS to perform overlay, intersect, and other change detection operations on new versus old data sets.

If the data is new, then append it to current information, if it involves a change, then perform a replacement operation. Historical information should be saved and archived for later modeling or comparative analysis. All transactions should be recorded in an audit buffer so the user can recreate a historical condition, should the need arise.

<u>Data Transfer & Data Load Strategies / Standards</u>

Developing a strategy to transfer and load data is an issue since delivering the data in a complete, concise and uniform method to the customer is the ultimate goal. See Section 3.3.2.5 for a review of the common graphics data exchange formats.

3.3.3.6 Storage and Compression of Data

Section 3.3.2.6 raises storage and compression issues and provides a comprehensive review of solutions. Please refer to this previous section for a more detailed discussion of this topic.

3.3.3.7 Ownership of Data

The ability for a company to provide a service that will coordinate updates from various data sources, apply them properly and distribute them in a timely manner is an integral part of the process. Jeppesen currently provides Aeronautical Data (Jeppesen NavData) to existing avionics firms for Flight Management Systems. Jeppesen is poised to perform this same function associated with Terrain, Obstacles and Airport data.

While Jeppesen is responsible for assimilating and accurately reproducing data, governments throughout the world are responsible for authoring data. Governments must be encouraged to stand behind the data they produce and ensure that it can effectively be used for SVS applications.

3.3.3.8 Certification of Data and the System

RTCA DO-200A provides the guidelines by which the process for data production and distribution is achieved (RTCA DO-200A, May 1998).The key ingredients are to have a well-defined and documented process that demonstrates configuration management, validation, and verification.

Having the process documented and then demonstrating that this process is adhered to and reproducible are also key elements that will be applied to a certification audit. Many product suppliers have Quality Assurance plans that lay the foundation corporate wide for such certification. Product suppliers have indicated that they are currently ISO certified and will also adhere to the DO-200A standard.

Certification for the actual SVS Application will have to be performed based on the required integrity level of the system. For SVS safety system applications, situational awareness and terrain / obstacle hazard alerting (i.e., backup system) are the primary goals and therefore demonstrating that the application performs according to specification for selected areas may be sufficient. This demonstration will most likely include flight tests.

For SVS tactical applications that are expected to actually navigate the plane, a much higher level of certification and demonstration will most likely be required. To mitigate the issue of extensive flight tests, highly accurate and consistent data will be required.

Data coming from a single proven source rather than from multiple sources with various degrees of accuracy and / or confidence will dramatically improve the ability to certify the system. However, single source databases must still have an independent collaboration with another reliable source in order to be accepted. For SVS tactical applications, data in the takeoff / landing phase is required with an accuracy that can currently be achieved only through satellite imagery (e.g., Spot).

The Shuttle Mission should also provide the accuracy and resolution required for SVS tactical applications and will provide a consistent global source for the approach / departure and enroute phases as well. While this is expected, it cannot be guaranteed. It is expected that the Shuttle data will be validated to ensure that it meets the expected

While having a single reliable source may mitigate certification of strategic and tactical SVS applications, it is unclear if flight tests at selected airports will be sufficient. It is suspected that no matter the confidence of the data, that certifying authorities may still require some extensive flight tests that could be very costly.

3.3.3.9 Liability

Liability is an issue since if negligence can be proven to contribute to an airline tragedy, the associated companies could be held liable. Liability cannot be eliminated but it can be mitigated by the use of validated, high integrity data sources and processes.

An organization that can demonstrate a certified process that ensures the data is suitable for the intended use and that no inadvertent errors can be introduced should be able to defend itsself in liability cases.

For SVS safety system applications, the probabilities are expected to be manageable. For tactical SVS applications where the data and the system are navigating the plane the issue is much greater. From a database standpoint however, having a reliable and consistent data source, especially one that is an official government source (Shuttle Mission) should enable this issue to be manageable.

Clearly however, any company that will choose to coordinate and distribute data for use in SVS applications will need to be certified at least to DO-200A standards, if not greater.

The issue of misuse of the system by a pilot that causes a tragedy is an issue that it is not clear how to mitigate. This becomes an implementation issue and could arise for instance if a pilot uses a situational awareness display to help navigate a plane

3.3.3.10 Processing of Multiple Sources

Processing multiple sources of data is an issue since having a process defined and proven that can combine multiple sources and produce a suitable model using all different combinations of inputs may be difficult to effectively demonstrate.

Some of the issues previously discussed such as validation and certification should help to mitigate this issue. If the resultant data can be proven to be suitable for it's intended use (validation) and the process by which the data is certified and reproducible, then it is possible that the issue of processing multiple sources no longer is an issue. A study is currently underway by the International Terrain Database Integrity Group (ITDIG) whose intent it is to study such a process and provide recommendations and guidelines for the most effective process for handling terrain data. RTCA committee SC-193 and EUROCAE WG 44 are also currently meeting to discuss terrain database issues.

Another method for mitigating the risk of multiple sources is to have a single reliable and consistent source that can also be proven to be suitable for the intended use. The Shuttle Mission is expected to provide a data set that could mitigate this issue assuming that it's goals can be achieved.

3.3.3.11 Data Conversion Between Different Systems

Converting data to a common datum is an issue when data is in different datums and sufficient conversion algorithms do not exist. The easiest solution to mitigate this issue is to mandate that all data will be provided using an international standard, e.g., WGS-84.

WGS-84 is used extensively for horizontal positioning, but mean sea level (MSL) is still used predominately for vertical elevations. MSL elevations can also be derived using unique datums, compounding the conversion problem. Conversion algorithms exist for most common datums and are readily available from NIMA associated with their MUSE product.

In addition, the Datum Transformation Coordinate Conversion (DTCC) program will convert between most common datums and the "GEOID" application will convert elevations from ellipsoidal to geoidal. From a database standpoint, having the data distributed using a common datum is essential. Issues may be encountered when dealing with sources that have an unknown datum. If it can be matched up suitably with other sources then a conversion can be possibly assumed. If not, then the data should be rejected.

On-board sensors and avionics instruments providing dynamic inputs to the SVS applications are another source of information that may need to be converted within the system. However, it is expected that these datums will be known and the appropriate conversion will be applied. The only issue could be for SVS tactical applications if the error rate for the conversion could present a data integrity problem. The conversion should be within the 10-meter accuracy required for the takeoff / landing phase, but may not provide the 1-meter accuracy required for airport. The Local Area Augmentation

System (LAAS) uses the WGS-84 datum and geoidal height to provide high accuracy navigation data to support the tactical precision approach operation.

3.3.3.12 Verification

Verification is a critical part of the data process needed to ensure that no inadvertent errors are introduced into the data. The simplest and most widely used verification technique uses cyclic redundancy codes (CRC), e.g., a 32-bit CRC error checking protection code to detect potentially corrupted data. This verification check is common with most compression algorithms and provides a high level of data integrity suitable for use by all applications. It is expected that this technique will be used throughout the database production process, with the storage of the data within the system, and with the use of the data in the SVS applications themselves.

3.3.4 Implementation Plan

Synthetic Vision applications have been defined for safety system, strategic and tactical purposes. The availability of terrain, obstacle and airport data to support these applications have been discussed along with other issues.

It is clear that the data to support all applications does not readily exist today for the entire world. The best and most complete data available today is within the United States as terrain and obstacle data are readily available to support Safety applications.

Outside the United States, terrain data is available with the exception of some mountainous regions that will require higher resolution terrain data for the approach / departure phase of flight. Obstacle data outside the United States however is not as readily available and the ability to obtain the obstacle data required is still very uncertain. Complete terrain data for the takeoff / landing phase is obtainable from satellite imagery, but at a huge cost. Data for the Airport phase is also obtainable, but the cost ($30,000 per airport) and timeliness to generate the airport data is also not feasible from a global perspective at this point in time.

Based on issues raised, the following are some thoughts on how SVS applications and associated data can possibly be implemented.

3.3.4.1 Incremental Implementation for Applications

Based on some issues being raised concerning certification, liability, validation and data availability, using the old adage “walk before you run” could apply here. Three different application areas have been suggested: SVS for safety systems, strategic and tactical use.

Since data, for the most part exists that will support safety system applications, it makes sense to implement these applications first, then as incremental enhancements, provide the additional functionality associated with the strategic and tactical applications.

In order to implement safety system applications, certification for the database process will have to be achieved. While systems can be certified according to the safety system application requirements initially, they must be designed to support the long-range goals for tactical applications as well. By implementing safety applications first, the industry can prove that a database can be built and proven to be suitable for the intended use and should establish the foundation by which the enhancements for strategic and tactical can be added.

3.3.4.2 Incremental Implementation for Data

With terrain data currently available to support the synthetic vision requirements for the enroute and departure / approach phases of flight, it makes sense to implement the process by which this data is maintained and distributed. With data for the takeoff / landing phase being somewhat cost prohibitive at this time, it may make sense to wait to see if the data from the Shuttle Mission will satisfy the takeoff / landing phase goals.

If the accuracy goals for terrain data (8 to 16 meters vertically) from the Shuttle Mission are achieved, then terrain data to support the takeoff / landing phase should then become readily available and be very cost-effective. As stated previously, one would also expect that with data from the Shuttle Mission becoming available, other satellite firms will offer "deals" for their data that could make obtaining their data more affordable as well.

<u>Note that this only addresses terrain data associated with this implementation. There is still a major issue dealing with the generation and maintenance of a reliable worldwide obstacle data set.</u>

3.3.4.3 Implementation by Geographic Area

Data is most readily available today within the United States that supports the enroute and approach / departure phases including both terrain and obstacles. An implementation option may be to implement the associated applications within the United States first, then as data becomes more readily available outside the United States, provide incremental updates to expand the geographic coverage.

3.3.4.4 Implementation by Airport

Lack of data support is prominent at or near the airport for the takeoff / landing and Airport phases. The Shuttle Mission is expected to provide sufficient terrain data that will satisfy the takeoff / landing phase.

The accuracy required for the Airport phase however is such that a prioritization by airport may be warranted. The cost and time required to generate this data set essentially dictates that only a limited number of airports can be generated per year.

Based on this, prioritizing by airports that would gain the most benefit from this data set makes sense. Over time, technology should improve to allow more cost and time effective generation of this data.

3.4 Database Integration and Processing Considerations

The previous sections examined availability of the various SVS databases and issues in acquiring high-integrity data to support the requirements of SVS applications. This section takes a preliminary look at the issues associated with integrating and handling of these SVS databases that are used in synthetic vision applications.

A conceptual database architecture is presented based on the inherent need for information layering of SVS data. This section also describes candidate information layering concepts from the perspective that this data would ultimately need to be handed off to a display graphics processing subsystem for real-time depiction of database information on the cockpit display. Integration / fusion of data is discussed within the database architecture and file system. This is followed by a discussion of display processing / graphics rendering of raster and geometric data.

3.4.1 Database Integration / Data Update Cycles

The candidate synthetic vision system (SVS) applications rely on a range of digital data products / databases from a variety of vendors. Integration of these various data sets into a single, cohesive, centrally managed database product is an important challenge for SVS. Each of the source data sets must comply with data integrity standards determined by the respective SVS applications, and each of the data sets must correlate with each other in order to avoid improper presentation and artifacts on the SVS display(s).

SVS databases comprise a number of thematic data layers including terrain, obstacle, cultural feature, airport, navigation, imagery data, etc. These thematic layers differ in their life cycles, or rate of change, in addition to other differences. These update cycle differences are shown in Table 3-5.

3.4.2 Information Layering

The thematic data layers described in section 3.4.1 represent the baseline data types of potential SVS applications. These data must be integrated together to form a real-time, integrated SVS database in support of SVS applications. This integration of data is typically accomplished by layering of the various information sources into an information hierarchy that supports the SVS applications and associated display processing. Complicating the integration of these databases / thematic data layers are a number of factors:

SVS Thematic Data Type	Approximate Update Cycles
Terrain Data	Years / Decades
Obstacle Data	Weekly / Monthly
Airport Data	Weekly / Monthly
Navigation Data	28 / 56 day IRAC
Imagery	Monthly / Yearly

Table 3-5 Approximate Update Cycles for SVS Databases / Thematic Data Layers

- Source data may originate from several data suppliers
  - May consist of various data formats
  - Source data may be obtained using various geodetic datums / reference frames for their true position
  - Different resolution and accuracy of data
  - Different levels of database integrity
- Thematic data layers / databases consist of unique data types
  - Terrain data typically consists of elevation posts using a specific grid spacing
  - Obstacle data are often represented as single elevation posts without a grid
  - Image data (also referred to as texture) consists of pixel / raster data
  - Cultural features, airport databases, and navigation databases may be depicted using geometric data (points, lines, polygons) or may be depicted as textures.
  - Other types / combination of data types may also exist
- Integration of various levels-of-detail (LOD) among database thematic layers

- Correlation / miscorrelation of various database thematic layers
- SVS information may be automatically selectable by the SVS application, and / or by the pilot. This dictates an ability to turn on / off individual information elements / data thematic layers.
- Etc.

In light of these differences, the proposed SVS database is structured as a **layered** design. This design choice preserves the independence of the thematic layers, while at the same time combining them into a consistent structure. The layering implementation is discussed in the next section.

3.4.3 Synthetic Vision Database Architecture

A conceptual SVS database architecture using an information layering approach is shown in Figure 3-1.

Reliability / Integrity Verification

From Figure 3-1 it is seen that a variety of independent data sources are integrated to form the layered SVS database. Section 3.3 described the role of database source providers and distributors in developing high-integrity data sets. This part of the database architecture / process is depicted by the cylindrical data sources and the gray reliability / integrity checking functional blocks. Regardless how these data sets were originally developed, it is assumed that the outputs are SVS databases that meet the data accuracy and integrity requirements of the intended SVS applications.

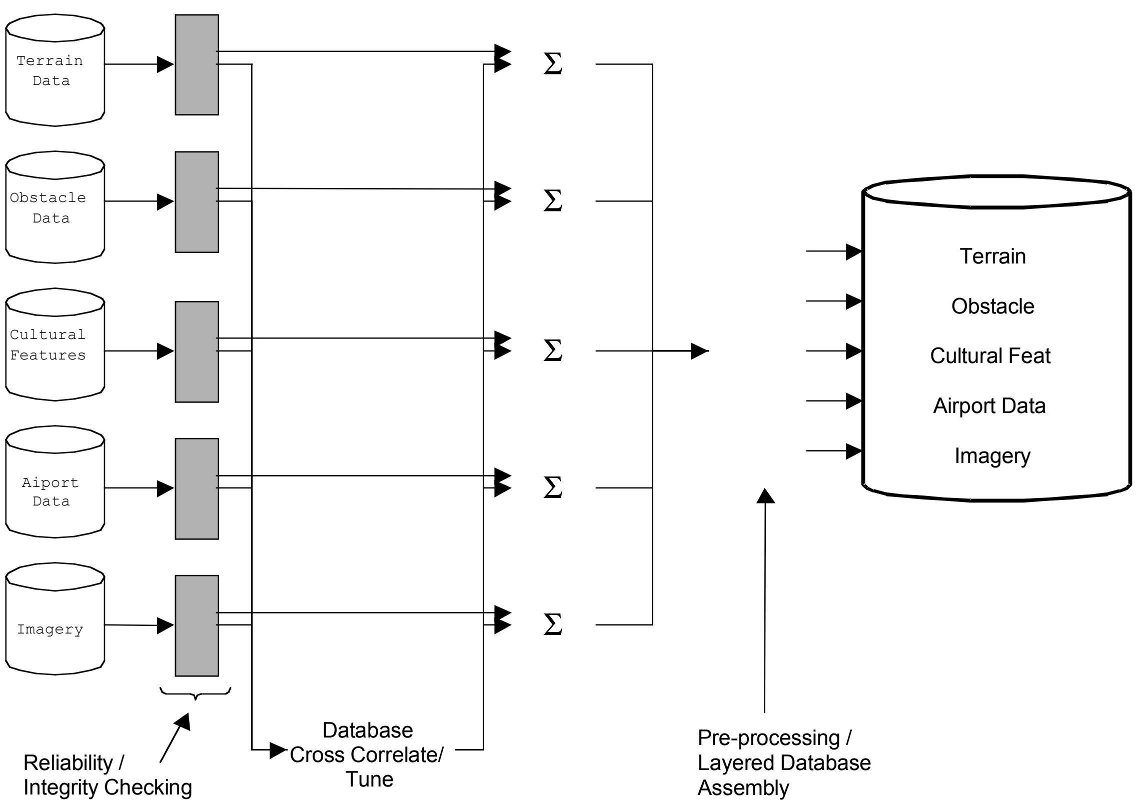

Figure 3-1 Layered Assembly of a SVS Database

Database Cross-Correlation / Tune

The next step in the database architecture is cross-correlation and tuning of the databases. In this phase, the source data types are integrated together and verified visually or using automation. For example, when obstacle data and terrain data are combined, the obstacles should merge correctly with the terrain surface; i.e., they should not hover above or fall below the terrain. In cases where they do, the anomaly must be tracked back through the audit trail. There are many sources of such an error. For example, different data sources may have been generated using differing datums / reference frames.

Verification and visual inspection of merged data may be performed by the data source provider, data distributor, or SVS avionics manufacturer. The avionics manufacturer may be receiving several data sets that are then integrated into the avionics system and associated SVS database development process. It is beneficial to seek automated verification methods whenever possible for ensuring data integrity.

Preprocessing / Layered Structure Assembly

Data at this phase of processing has been independently validated, and verified to correlate with other data types that it will merge with. It is at this phase that a common, layered database structure should be assembled. The individual data layers of the layered structure are depicted in Figure 3-1. At this point in the architecture, any inconsistency in data formats is resolved and converted to common formats. The correlated / tuned database layers are assembled as separate, parallel assembly paths, i.e., layers.

Due to the expected computational burden on the real-time synthetic vision system, the database should be optimized for real-time processing. By prestoring multiple levels-of-detail of each data type (i.e., information layer), and allowing rapid selection of data via a switchable data selection hierarchy, the SVS can quickly select the appropriate mix of data to be combined and processed into displayable information. Due to large amounts of data, data compression is used to reduce storage requirements.

Upon assembly, each layer in the database forms a logical partitioning of data elements. An advantage is that individual layers can be updated independently. Some layers, such as airport data, may require more frequent updates than other, more static types such as terrain. The database layers are separate, but lumped together in the core database structure, where they are stored in local permanent storage media, such as a high-capacity disk.

Throughout all processing in Figure 3-1, a rigorous process of validation and verification of data is required by the industry. This is needed to support the high-integrity requirements of the SVS data system.

3.4.3.1 Paging

At run-time, the database is loaded into local system memory for use by the SVS application(s). A specialized software module called the **loader** reads the database from disk into a memory structure called the **scene graph**. The scene graph is periodically paged by the loader. That is, only the portion of data relative to the current display viewpoint, or eyepoint, is loaded into the database. A pictorial description of paging based on eyepoint is shown in Figure 3-2, which indicates the importance of spatial organization of the database, called **paging**. When the eyepoint leaves the current page or tile, it is "paged out" and another tile is "paged in".

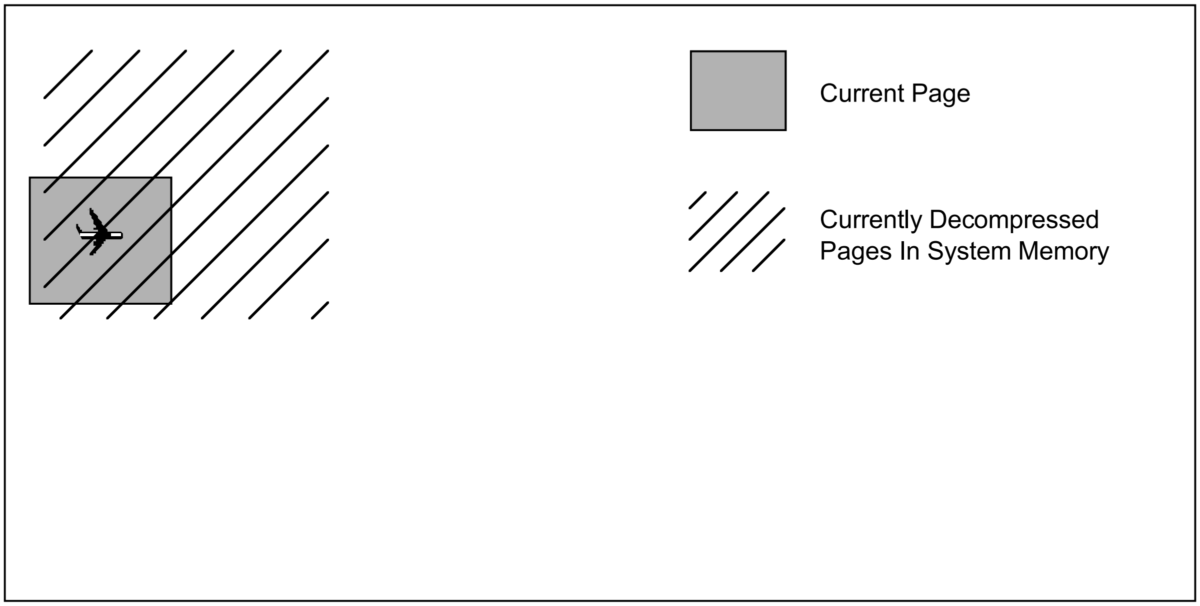

Figure 3-2 Database Paging Based on Display Viewpoint

3.4.3.2 Database Structure

The run-time SVS application requires a snapshot of the database in memory at every **frame**, where a frame is the rate of display update. For example, if the display application is running at 30 Hz, the **traverser** function in the SVS processor parses the database at 30 times a second to provide data to the display processing / graphics rendering engine at the 30 Hz frame rate.

The traverser walks through the scene graph each frame. The traverser decides what should be drawn based on current eyepoint location, viewing frustrum, occlusion, and based on the particular elements that the SVS application wants to display. Typically many elements of the scene graph may be **culled out** since they don't need to be drawn. **Culling** in turn increases real-time performance. The traverser needs to walk through each layer of a layered database. Parallel traversers are recommended if greater computational performance is required.

<u>Spatial Organization with Quad Trees</u>

During the assembly phase of database processing, spatial organization is a good strategy. The paging / tiling organization mentioned above is desirable because it leads to efficient database paging.

A successful spatial organization structure that is common for large databases is called the **quad-tree**. In this type of data organization, the parent mesh is subdivided into 4 meshes that contain 4 sub-mesh tiles. Each of these 4 meshes is further subdivided into 4 sub-meshes, and so on, until the desired level of database granularity is achieved. A quad-mesh structure is shown in Figure 3-3.

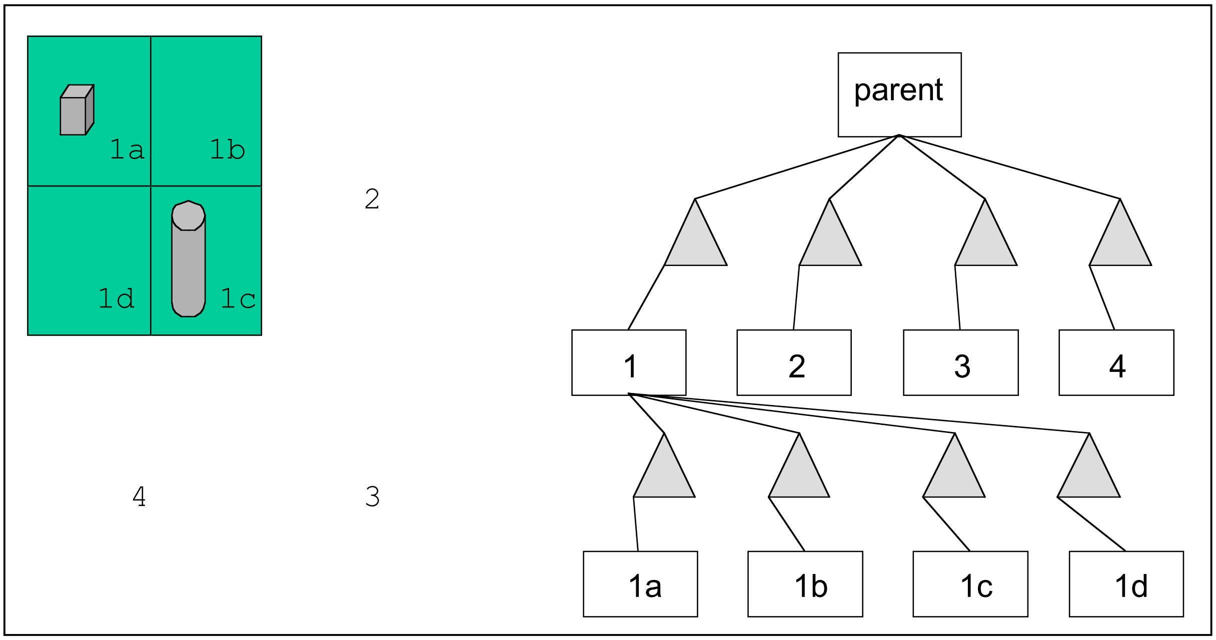

Figure 3-3 Quad-Mesh Database Organization

3.4.3.3 Levels-of-Detail

The spatial organization is also the required structure for setting up efficient **levels-of-detail (LOD)**. Most objects contain detailed features that become visually insignificant when viewed from a distance. Examples are trees and bushes on a terrain. When the eyepoint is near the target terrain, detailed models of the vegetation add to realism of the scene. At a distance of many nautical miles, these details become visually insignificant. It is inefficient from a processing perspective to attempt to draw these vanishing details. A good database LOD organization contains multiple models of a particular tile, each of which has an associated visual range of view.

The highest LOD contains the most polygons. Lower LODs contain fewer polygons. A good rule of thumb is that each successive reduced LOD should contain 70% of the polygons of the preceding level.

LOD switching can be envisioned as layers of invisible range spheres around the current eyepoint as shown in Figure 3-4. As the pilot's eyepoint, or display viewpoint, moves through the database, the range spheres do so also. Whatever falls within the innermost sphere is rendered in highest level of detail (HLOD). Whatever falls outside the low level of detail (LLOD) sphere is rendered in the least detail. Intermediate levels of detail lie in between e.g., medium level of detail (MLOD). LODs demonstrate why processing load increases when the aircraft approaches the ground, such as in landing scenarios. When the airport comes into the HLOD range sphere, many more polygons must be processed.

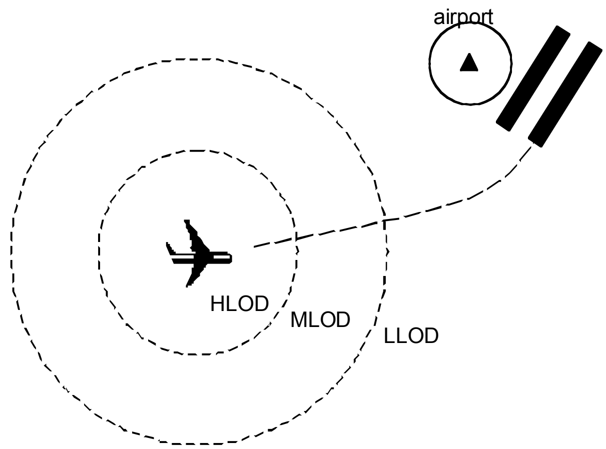

Figure 3-4 Level-of-Detail Organization of a SVS Database

As the eyepoint moves through the database, invisible range spheres “touch” different parts of the database relative to the eyepoint. Parts of the database falling within the innermost sphere are rendered in full detail.

<u>Special Level-of-Detail (LOD) Considerations with Terrain</u>

Terrain is typically the most polygon intensive aspect of a visual database at a given altitude. In SVS database applications, a wide area of terrain may need to be processed. There are two primary methods of managing LOD in a large database. The first method is to create the LODs off-line and build them into the database structure. This method keeps multiple parallel copies of the database in memory, switching LODs in and out as needed.

The second method is to use active surface processing algorithms (Lindstrom, et al, 1997) which dynamically manage LOD and at the same time preserve feature and shape. This approach has the advantage of large reduction in the number of polygons rendered, and smooth, continuous changes between different LOD. It also has the advantage of improved storage requirements, since all the LODs need not be stored in memory. This technique is becoming more prevalent in the visual simulation industry, and warrants consideration for potential SVS applications.

3.4.4 SVS Display Processing / Graphics Rendering Considerations

This section provides an overview of display generation and the graphics pipeline associated with SVS applications. As indicated in the previous section, the SVS database architecture consist of layers of SVS thematic information such as terrain, obstacles, cultural features, airport data, navigation data, and imagery data. These layers are integrated in a hierarchical fashion to allow rapid selection and switching of level-of-detail data sets that are then input to the graphics pipeline to provide the display processing and rendering to generate the display image. While not discussed in this report, additional database information related to weather and traffic can also be integrated in the graphics processor.

SVS graphics processing must be capable of processing a variety of data types, including terrain grid data, texture / image raster data, and geometric / vector data. Figure 3-5 provides a functional description of a typical graphic processing system.

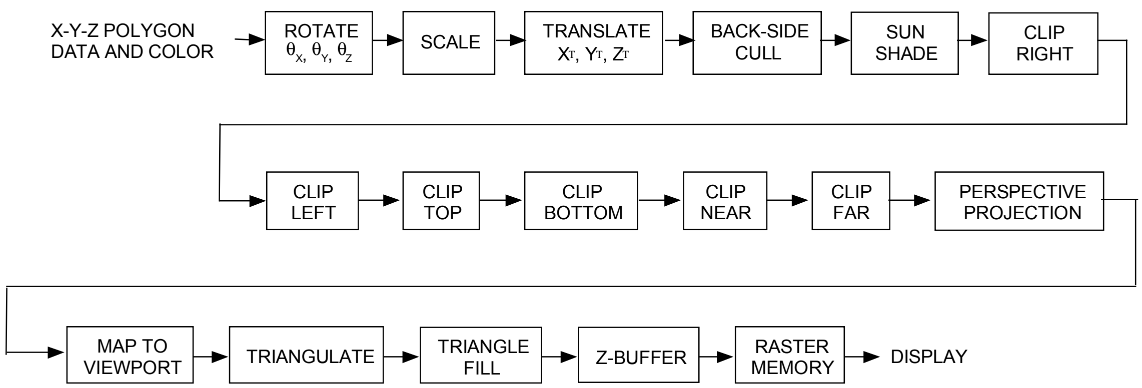

Figure 3-5 Typical Graphics Pipeline

From Figure 3-5, depending on the viewing angle (based on aircraft position, attitude, and viewing distance), polygons represented by vertices in the x, y, z coordinate system are rotated, scaled, and translated into the appropriate world coordinate orientation. Back-side culling eliminates polygon sides that are not visible. Sun shading is computed to provide the proper shading for the visible surfaces. The geometric image is then clipped into the display viewing area. After clipping, the 3-D perspective transformation is computed and mapped to the viewpoint. Polygons are then converted to triangles. To this point in the graphics pipeline, computations are on a per vertex basis using floating point math.

After triangulation of polygons, computations are performed on a per pixel basis using integer arithmetic. Triangles are filled with appropriate shading, color, or texture (including image data) as determined by the application. The filled triangles, i.e., raster image is applied to the z-buffer, where hidden surface are removed. The output is applied to the raster memory, also called the frame buffer, which drives the display, typically at a 30 Hz rate.

Merging of Display Image Data / Multiple Graphics Pipelines

For SVS applications, multiple data types are combined in the displayed image. Terrain data is often represented as elevation posts at using uniform grid spacings. A common way to depict terrain is to use the end-points of the elevation points as vertices and then convert them into terrain surfaces depicted by triangles. Geometric data is computed as points, lines / vectors, or polygonal surfaces, which are then processed as described above. In addition to these data types, textures may be applied to polygonal / triangle surfaces in order to enhance the SVS image. Textures may consist of shading or could represent a photographic image. It is in this way that image data can be draped over triangulated terrain surface to provide a realistic depiction of the outside scenery.

Preliminary System Requirements for Synthetic Vision

In order to develop a complex SVS image (e.g., a multi-layer image of terrain, weather, traffic, 2-D or 3-D geometric symbology, etc.) it may be necessary to utilize multiple graphics pipelines in parallel. One graphics pipeline may be dedicated to generating the terrain scene, while another graphics processor may be processing 2-D and 3-D anti-aliased foreground symbology. The outputs of graphics pipes are then merged in the raster memory / frame buffer for output to the display, typically at the 30 Hz frame rate.

Note: If SVS applications demand high computational requirements, implementation of the graphics processing system will require use of state-of-the-art, high-speed processors, memories, and application specific integrated circuits (ASICs). The graphics processing system can also ensure high-end performance by using advanced architectures that eliminate bottlenecks in bus interfaces, memory utilization, etc. Parallel architecture should be utilized if processing power is an issue.

The next sections provide several examples of sample calculations pertinent to SVS graphics processing. These calculations are offered to provide a perspective of SVS display processing.

Example #1 – Display Pixel Calculation

This calculation demonstrates how pixel rate is computed for a typical display scenario.

Assumptions: 1) Display screen size is 1024 x 768 pixels
2) Scene depth complexity factor = 3
3) Frame rate = 30 Hz.

Pixel rate = (1024 x 768) pixels x 3 x 30 Hz = **70 million pixels / second** updated.

State-of-the-art graphics generation: ~180 million pixels / second.

Example # 2 – Number of Terrain Triangles for a Display View

Assumptions: 1) Display viewing angle is 60 degrees (i.e., 1/6 of a full circle)
2) Viewing range is 20 nmi
3) Terrain database resolution (i.e., grid spacing is 100 m)

Display Area = 4 x π x (20 nmi)^2 = 200 square nmi
Terrain posts per nmi: ~ 20 post / nmi; in 400 squares or 800 triangles per square nmi.

Total number of triangles displayed per second for 30 Hz frame rate =
200 square nmi x 800 triangles / square nmi x 30 Hz
= **4.8 million triangles per second**:

State-of-the-art graphics generation: In range of ~1 to 3 million triangles per second.

Example exceeds capability of state-of-the-art. This example points out the need for more efficient terrain triangulation.

The above example depicts triangles for each elevation post, thus providing many terrain surfaces. For regions with relatively flat terrain, the number of triangle surfaces needed to depict the terrain can be reduced considerably. One approach uses Triangular Irregular Networks (TINs), where for a given vertical error bound, vertices associated with terrain posts can be merged into a much smaller set of vertices, since many of the vertices are co-altitude. This greatly reduces the number of triangles required to accurately depict the terrain. It is not inconceivable that a 95% reduction of triangles can be achieved using TIN for relatively benign terrain. Using the above example, a 95%

reduction of 4.8 million triangles per second results in a ~240,000 triangle per second update rate, well within the capabilities of available devices.

Additional Comments About TIN:

Note 1:

Mountainous regions such as the Sierra Nevada in California can be accurately represented with TIN using ~25 triangles / square nmi. For the above example (using 20 nmi viewing range), this results in 200 square nmi x 25 triangles / square nmi x 30 Hz = 150,000 triangles / second.

If viewing range is increased to 100 nmi, TIN-based triangle update rates for this region increase to 3.75 million triangles / second.

Note 2:

The concept of level-of-detail (LOD) was discussed earlier indicating that close in viewing areas require greater LOD, while far away areas use lower LOD. Conceptually, one can partition a cockpit display into several regions of LOD, i.e., a HLOD at the bottom of the display near the pilot's viewpoint, MLOD in the middle of the display, and LLOD at the top of the display. Further, if each region is represented by TIN terrain triangles, the number of triangle updates could be reduced considerably.

However, this approach has a significant problem: TINs take considerable computation time, and each time the viewpoint changes even slightly, the various TIN LODs must be recomputed. In addition, at the boundaries of the LODs, TIN vertices must be stiched to avoid popping artifacts from occurring on the display, i.e., avoid unbounded triangles. This approach is not practical with current graphics processing technology.

To overcome this problem, the entire display should use only one LOD at a given time. TINs for the various LODs can be precomputed and stored, and switched in as determined by the display range. When TIN LODs are changed, to avoid a sudden noticeable change, one may consider fading in the new terrain LOD TIN terrain and fading out the old LOD TIN terrain to ensure a smooth transition to the change in display view.

Example # 3 – Display Pixel Resolution

A typical D-size avionics display, with an active display area of 6.8 x 6.8 inches. Assuming 100 pixels per inch, the following distance is portrayed by each pixel, when a minimum viewing range of 2.5 nmi is assumed.

Distance / pixel = (2.5 nmi x 1852 m per nmi) / 6.8 inch = 681 m per inch, which is equal to 6.81 m per pixel. Thus this number illustrates the minimum distance resolution that can be represented by a single pixel. Of course, one human factors issue is the extent that the human eye can discern / resolve displayed information. Typically, the minimum perceptible visual angle for character recognition is ~ 5 to 6 minutes of arc.

In summary, many factors influence the how SVS information can best be displayed in a manner that is beneficial to the flight crew. Aircraft orientation, viewing angle, viewing distance, size of the display, and level-of-detail, all have a role in the quality of the displayed image. These same factors also have a significant impact on the computational complexity and workload of the graphics generation system.

3.5 SVS Databases – Top-Level Conclusions

This section summarizes the database discussions in the previous sections and summarizes top-level conclusions concerning the issues, mitigation alternatives and implementation plan for future SVS database developments and subsequent utilization by SVS applications. Top-level conclusions are as follows:

- The data to be derived from the Shuttle Mission appears prominently throughout this report section, as it is expected that this new data source will provide a much more accurate, resolute and affordable data set than is available today. Note again that this is for terrain data only. There is still a major issue with the generation and maintenance of a reliable worldwide obstacle data set.
- Terrain data, for the most part is available that will support applications in the enroute and approach / departure phases of flight.
- However, to support the takeoff / landing phase the Shuttle Mission is currently being relied on heavily to provide a cost-effective solution for terrain data.
- For the airport (i.e., surface operations) phase, it is expected that it will be some time before a global, cost effective and timely solution can be found to obtain a worldwide high-resolution / high-accuracy / high-integrity airport database solution. It is likely that for the near term, a limited implementation can be achieved by using photogrammetry and GIS.
- Certification is and will remain a major issue for SVS applications. It is still unclear how difficult it will be to certify a strategic or tactical SVS application. This could provide the biggest and most costly hurdle for the industry to overcome.
- It is important that the aeronautical industry define rigorous processes and standards for handling the high integrity and accurate data required by SVS applications.
- A cost estimate summary for development / acquisition of SVS databases is summarized in Table 3-6 below. Total cost to develop this data is approximately ~$54.5 million.

SVS Terrain Database Flight Phase Requirement	Estimated Cost	Comment
Terrain for Departure / Approach phase (6-arc second data at not currently provided by Airport Safety Model Data (ASMD), vertical accuracy of 30 meters)	~$1000 per airport	~250 airports affected Note: If vertical accuracies better than 30 meters are required, use satellite imagery at ~$10,000 per airport (10 m vertical accuracy)
Terrain for Takeoff / Landing phase (6-arc second ASMD does not support vertical accuracy of 10 meters)	~$10,000 per airport	~450 airports affected Require satellite imagery to achieve vertical accuracy of 10 meters)
Satellite Imagery terrain for Takeoff / Landing phase (37 x 37 square kilometers)	$10,000 per airport	$50 million for 5,000 IFR airports worldwide
Airport database for Airport / Surface Operations	$30,000 per airport	Only Atlanta and Denver have been surveyed (requires photogrammetric techniques, conversion to vectors / GIS themes)

Table 3-6 Summary of Estimated Terrain Database Source Development Cost

3.6 Key SVS Database Issues

As is evident from this Section 3, there are many issues that pertain to the SVS database(s). These are discussed to varying levels of detail and are summarized here. Refer to the previous sections for more detail concerning the individual issues.

The key SVS database issues are:

- Need for a rigorous process and standards in the development and use of SVS databases in avionics systems.

  RTCA DO-200A / EUROCAE ED-76 standards are current process standards for aviation databases. Due to the prospects for higher integrity requirements for SVS databases, industry must upgrade the current standards

  - Data source supplier(s) must develop and utilize several, independent, high-quality "truth" data sets for validation and integration into high-integrity databases for SVS use
  - Data distributor(s) that provide value-added data processing to SVS databases must follow a rigorous process to assure that they maintain the data integrity of the source providers. When integrating several sources of data, the distributor in essence becomes a source supplier of a new, integrated data set, that must follow a process similar to that of a data source supplier
  - SVS system developers, i.e., avionics manufactures, must follow a rigorous process in accepting and using SVS databases obtained from data source suppliers and data distributors, and are responsible for assuring SVS system integrity
  - The SVS end-user, i.e., airlines / pilots, are responsible to follow the process of data loading and updating integrity databases to ensure that system integrity is maintained. In addition, end-users must only use the SVS system in a manner consistent with the intended function / system integrity.
- Need for standard database message formats and data exchange standards for the various data types (grid posts, image data, geometric / vector data, etc)
  - Needed to maintain integrity of database process
  - Needed to contain / minimize cost of data handling, update and dissemination.
- Current SVS data sets / databases are rather limited in integrity. Future applications will require expanded / additional validation of data to ensure higher database integrity.
- "Truth" data is needed in the development of high-integrity databases! How do we obtain "truth" data / what is acceptable "truth" data?
  - Very important for generation of high-integrity databases / validation of data.
- Terrain database issues
  - Enroute phase: Required grid resolution is in range of 30 arc-seconds to 150 arc-seconds. Actual requirement depends on intended use. To support EGPWS / GCAS and current terrain separation standards, 150 arc-second data should be adequate. While not immediately available, 150 arc-second data can readily be obtained form available 30 arc-second DTED Level 0 data

  - Departure / Approach phase: For mountainous airports, Airport Safety Model Data (ASMD) with 15 arc-second grid spacing is not available for some non-US airports. Estimated cost to obtain data is $1,000 per airport, ~ 250 airports not available at this time
  - Takeoff / Landing phase: 6 arc-second ASMD data available for all 100 US airports that are "terrain-challenged". Only 100 of 350 "terrain challenged" international airports outside the US are available

    In addition, ASMD data is only available at 30 m vertical accuracy. If this type of accuracy is inadequate for the takeoff / landing phase, i.e., 10 m vertical accuracy is needed, then all 5,000 IFR airports worldwide will require resurveying of terrain data. Satellite imagery data at $10,000 per airport is likely required ($50 million worldwide)
  - Airport phase: Detailed survey of airports and conversion into GIS themes is estimated to cost $30,000 per airport. Only Atlanta Hartsfield and Denver International airports have been mapped
  - The Shuttle Mission is expected to provide a much more accurate, resolute and affordable terrain data set than is available today
  - The Shuttle Mission is currently being relied on heavily to provide a cost-effective solution for terrain data for the takeoff / landing phase.
- Obstacle database issues
  - Availability of accurate and reliable obstacle data is severely lacking, particularly outside the US
    - NIMA maintains a worldwide obstacle database of about 300,000 obstacles. These do not represent a complete database of obstacles and are only the tip of the iceberg
    - One must sweep all airports of obstacles before conducting high-integrity SVS applications / operations
  - The National Geodetic Survey provides very accurate and complete surveys of obstacles at airports for FAA using FAA Document 405 as a guideline. Unfortunately only ~900 airports have been surveyed to this standard. Availability of worldwide obstacles data to this standard is severely lacking. To obtain this level of accuracy for worldwide airports will be very costly and a long-time undertaking
  - Enhanced development of a worldwide obstacle database is absolutely required for planned SVS applications. An effort through international standards organizations such as ICAO must be undertaken

    It can be assumed that obstacle data for many parts of the world cannot be obtained even through these organizations. The only alternative means of obtaining obstacle data for these places will be via satellite imagery or aerial photography
  - Unlike for terrain data, the Shuttle Mission goals do not include generating obstacle data. The Shuttle Mission will include a "vegetation bias" that will be a part of the data. Buildings could be included with this bias. Smaller obstacles such as towers however will not be evident enough to be derived from the shuttle

or other satellite imagery, especially for the vertical dimension. Obstacles may be evident for their latitude / longitude position, but will require resurvey to obtain accurate vertical accuracy

- Update of obstacle data is a significant issue. While terrain data is relatively static, obstacles can be erected in relatively short time. To maintain accurate and reliable updates of obstacle will require great vigilance and a sophisticated update process.

- Airport database availability
  - Requires local aerial photogrammetry that can survey the airports to 1-meter accuracy as required. The current cost per airport is very costly at ~$30,000 per airport
  - It is expected to be a time-consuming and expensive undertaking to obtain an extensive set of airport data. However, in order to support the future SVS applications, processes and infrastructure to generate and manage this data must be developed
  - New mapping technologies using photogrammetry and conversion into GIS are immerging, which may help reduce cost in the future.
- Cultural feature availability
  - V-Map Level 0 (source of cultural feature data) cannot support the accuracy required around airports. More detailed data will have to be defined from local airport / aerial surveys as required for airport data.
- Release of high-resolution data:
  - The Shuttle Mission promises that DTED level 1 (3-arc second, 100 m grid) terrain data will become available for non-military users. Due to the potential military use of such data, there is a concern that NIMA may not release this data
  - There is also an issue of sovereign countries allowing the release of such data.
- Liability considerations concerning SVS databases
  - Presently, government terrain and obstacle data source providers use disclaimers that they do not stand behind the data they provide due to liability concerns. In the future, if high-integrity databases are the end-goal for SVS use, government and industry data providers must work together, using best commercial practices to reduce liability concerns, and stand behind their data
  - In addition to data source providers, data distributors, avionics manufacturers and SVS end users must follow a rigorous data handling process to best commercial practices to mitigate liability concerns. All parties must stand behind their products and share liability.
- Storage of SVS databases is an issue
  - Large storage capability with fast access is required
  - Fast and lossless data compression with high compression ratios is needed
- Database update issue
  - Update strategies could employ several techniques, including:

    - Development of a network of information providers, vendors, airports, regional or local / municipal government agencies, aviation industry sources, etc. to relay change information based on a set of business rules or criteria that effect the flight information database
    - Establish a temporal data refresh schedule and capture digital orthoimagery and / or surface vector / raster geospatial information and use the power of GIS to perform overlay, intersect, and other change detection operations on new versus old data sets
    - How much data should be stored in aircraft? Tradeoff between mass storage, dataloading of large files during preflight, and datalink uplink only those data that require frequent updating to conserve datalink capacity.
- SVS database architecture and display generation issue
  - Many fine grained issues exist that related to implementation of the real-time SVS applications using a database file system / data integration (information layering), level-of-detail processing, information storage, graphics generation / display rendering, etc. This is primarily concerned with design / development of the SVS system. Section 3.4 discusses this topic in more detail.

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4.0 Aircraft Integration of Synthetic Vision

This section examines issues pertaining to the integration of synthetic vision applications, identified in Section 2.5, into in and out-of-production commercial and business aircraft.

In the following subsections, a list of presently available equipment related to Synthetic Vision System (SVS) applications is identified. This list is used to query the available equipage database in order to identify the SVS related equipage of aircraft in the fleet. The equipage database includes airline and business aircraft operated in US airspace and represents a good sample of the worldwide fleet with the exception of the fleet in the former Soviet States.

The list of identified equipment is further analyzed to determine if it can support the proposed applications.

4.1 Synthetic Vision Avionics Requirements

The following type of avionics equipment are considered relevant in supporting SVS applications:

Function	Avionics System
Navigation	FMS
Sensors	DME, GPS, WXR, LORAN, VOR, NDB, ILS
Synthetic Vision Processor	EFIS
Display	CRT or LCD, HUD, WXR, TCAS
Database Storage	FMS Database

Table 4-1 Equipment to Support SVS Applications

Weather Radar is included as a potential position sensor as well as display. The WXR in its present form cannot accurately provide position information (only a limited situational awareness capability) but with the proper radar reflectors on the ground it is potentially feasible to get more accurate position information during approach and landing.

The majority of the display systems presently available process most of the data in a separate processing unit while relying on some graphical processing in the display head itself.

DME equipped aircraft are capable of achieving significant position accuracy that may be sufficient to drive synthetic vision applications enroute. The data presented below assumes that all FMS equipped aircraft have a DME sensor on board capable of auto-tuning multiple DME stations.

GPS provides sufficient accuracy for cruise but is unlikely to support any synthetic vision applications associated with precision approach. Differentially corrected GPS (DGPS) will be required for such applications. There is currently no aircraft equipped with differentially corrected GPS receivers.

LORAN is a long range navigation sensor used by FMS in conjunction with other navigation sensors such as DME, VOR and GPS. LORAN has recently gained support as a complementary sensor to GPS. These two dissimilar systems will mitigate against hazardous interference effect, either inadvertently or deliberately, which is an essential characteristic of any safety-critical system. Prior to that, LORAN was mostly used where the ground-based radio navigation infrastructure was insufficient. As a result very few air transport, regional and business operators in the US airspace are equipped with LORAN. In fact, our survey of air transport and regional operators, did not identify any aircraft equipped with such a sensor.

The only data storage device currently available on aircraft is used for storing FMS navigation databases and flight plans. It is assumed that all FMS have such a database. It is highly unlikely that this storage device would provide sufficient storage for synthetic vision application. The FMS database criticality level is assumed to be essential. The SVS database may be of a higher classification depending on its intended use.

4.2 Survey of Current Avionics Capabilities

This section identifies the percentage of aircraft equipped with avionics systems identified in Section 4.1. The data was derived from a database that includes all US air transport and regional aircraft as well as a limited number of US business aircraft. Although this database is limited to US airspace users, it does provides a good representation of the worldwide[1] fleet of commercial and business aircraft. This database was last update in 1997 and therefore it does not reflect aircraft that may have entered or have been removed from the fleet since then.

The aircraft fleet was subdivided into three groups based on the type of the primary cockpit instruments:

Group 1: EFIS Integrated
This group includes aircraft with CRT or LCD displays that integrate multiple primary airplane parameters onto one display, typically referred to as the Primary Flight Display (PFD) and navigational data onto another display, generally referred to as the Navigation Display.

Group 2: EFIS Separate
This includes aircraft that utilize CRT displays to perform the function of the primary mechanical instruments such as the HSI and ADI. These displays are generally smaller in size than those found under group 1.

Group 3: Electromechanical
Aircraft in this group have electromechanical instruments but may have a CRT or LCD display that is associated with a weather radar system and / or TCAS.

The tables below list the aircraft models and number of aircraft in each group and provide the respective percentages of relevant avionics equipment found in each aircraft model.

[1] Excludes former Soviet States and is biased toward US airspace operators when it comes to mandated equipage such as TCAS.

Aircraft Type & Model	# of Aircraft	Weather Radar	HUD	FMS	GPS (GNSS)
A319/A320/A321	92	2%[2]	0%	100%	2%
A310	56	100%	0%	100%	0%
B 747-400	40	100%	0%	100%	75%
B 777	16[3]	100%	0%	100%	100%
B 737-600/700/800/900	0	100%	0%	100%	100%
Canadair RJ	25	100%	2%[4]	100%	2%
Fokker 70/100	133	100%	0%	100%	0%
MD-11	59	75%	0%	100%	0%
SAAB 2000	24	100%	0%[3]	100%	0%
Starship	50	100%	0%	100%	40%

Table 4-2 Group 1: EFIS Integrated (PFD, ND, MFD)

In Group 1, all aircraft types are equipped with an FMS and weather data. Only a limited number of aircraft models are equipped with GPS. Only two models are equipped with a HUD as most aircraft models in this group are Cat III capable. Weather data is typically displayed onto the navigation displays thus there is no need for a separate weather radar display.

Aircraft Type and Model	# of Aircraft	Weather Radar	HUD	FMS	GPS (GNSS)
ATR-42/72	173/81	100%	0%	0%	0%
A310	56	100%	0%	100%	0%
B 737-300/400/500	725	100%	20%	100%	13%
B 757	460	100%	0%	100%	45%
B 767	202	100%	0%	100%	48%
MD-80	668	24%[5]	0%	24%	0%
MD-90	17	100%	0%	100%	0.5%

Table 4-3 Group 2: EFIS Separate (EADI, EHSI)

Group 2 includes the most popular aircraft models. These aircraft are generally equipped with FMS and weather radar. Only a large number of B737 are equipped with HUDs. The number of aircraft with GPS is relatively low although their number is increasing based on recent data.

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[2] Low number due to insufficient data in database
[3] Includes a Multi Function Display (MFD) as well as a side display (optional)
[4] Non-US operators have 40 SAAB 2000s and 65 Canadair RJs equipped with HUDS
[5] To simplify the database, all MD-80 models were lumped together in one group. Many of the older MD-80 did not have glass cockpits.

Aircraft Type and Model	# of Aircraft	Weather Radar	HUD	FMS	GPS (GNSS)
Bae Jetstream 31/32	219	45%	0%	45%	44%
Beech 1900	400	100%	0%	.5%	0%
B727	923	100%	9%	5%	7%
B737-100/200	406	100%	18%	2%	0%
B747-100/200/300	160	100%	0%	9%	19%
De Havilland Dash 8	158	30%	28%[6]	30%	30%
EMB-120	234	100%	0%	0%	0%
Dornier 328	41	0%	0%	0%	0%
Metro III	94	0%	0%	0%	0%
Fokker F27	35	31%	0%	0%	3%
L-1011	80	52%	0%	52%	52%
DC-10	168	100%	0%	0%	6%

Table 4-4 Group 3: Electromechanical

Group 3 includes many more aircraft models than there are listed in the above table. The most popular models are only included for simplification. A considerable number of aircraft models appear to have weather radar on board but a much smaller number is equipped with FMS. A number of aircraft have GPS on board. This is a group where most GPS based FMS navigators can be found. A significant number of two specific aircraft models are equipped with HUD.

Group 1 represents approximately 6% of the total US fleet. Less than 1% of the fleet is equipped with large LCD displays (B777 and new Generation B737). The number of LCD equipped aircraft will increase significantly over the next few years as many Boeing models (B767, B717) as well as all Airbus models are scheduled for cockpit upgrades that call for the installation of such displays. Approximately 28% belong to Group 2 while the overwhelming majority (66%) are equipped with electromechanical instruments.

4.2.1 Characterization of Displays

Displays can be characterized by the following attributes:

- ***Display Type (technology)***

  CRT displays are the most popular technology. The majority of these displays are of size A (5.5 x 6 inches) or B (6.0 x 6.25 inches). Only a few aircraft models have large D-size CRT displays and even a smaller number have LCDs.

- ***Display Configuration***

  This simply describes how the displays are configured in the cockpit.

[6] Although it is known that 45 aircraft have been equipped it is unclear from the survey how many are operating in the US.

- ***Display Size***

  Typically type A and / or B-size displays are used as an EHSIs, EADIs or weather radar. The large format displays are approximately 8 x 8 inches. The effective display area is less.

- ***Capability (display writing method)***

  All CRTs currently available are color "stroke and raster" displays. HUDs have only stroke capability. LCDs are bitmapped devices.

- ***Refresh and Update Rate***

  The update rate is normally determined by the parameters being displayed. The highest data update rate is 20 Hz and applies only to a limited set of parameters. The typical screen refresh rate is much higher and it varies between 60-80 Hz. LCDs on the other hand have a fixed update rate of 60 Hz.

- ***Resolution (number of RGB pixels per inch)***

  The CRT shadow mask typically has openings that are spaced 0.3 mm apart. This distance determines the CRT pixel spacing. The resulting resolution is anywhere from 60 to 85 pixels[7] / inch. LCD display resolution is typically in the range of 135 pixels / inch. Higher resolutions are advertised.

- ***Intelligence (display head processing capability)***

  This identifies the "intelligence" of a given display. "Dumb" displays must be provided with pre-processed data on a pixel-by-pixel bases and rely on the driver to do all data processing and graphics. Highly intelligent displays contain a graphics engine and need only to accept raw data. Most of the displays currently in operation have limited display processing capability and are referred to as "literate" displays.

- ***Interfaces (data delivery medium to the display head)***

  Most display drivers interface with the display head via video, ARINC 429 or ARINC 453 bus. The ARINC 429 bus has a limited capacity (approximately 100 kbits / sec) while the ARINC 453 bus can transfer data at the rate of 1 Mbits / sec. Although each display receives redundant bus inputs, it is typically only capable of listening to only one bus at a time. Therefore the interface is limited by the bandwidth of the existing busses.

The following table summarizes several of the display characteristics of EFIS and non-EFIS equipped aircraft.

[7] A pixel as it is defined here consists of a Red, Green and Blue element.

Aircraft Type	Type & Configuration	Size (inches)	Capability	Refresh Rate / Update Rate	General
A310	CRT		Stroke & Raster	70 Hz/NA	
A320	CRTs, 5 across	7.25 x 7.25	Stroke & Raster	70 Hz/NA	
B 737-300/400/500	CRTs EADI over EHSI	EADI: A size (5.5 x 6) EHSI: B size (6 x 6.25)	Stroke & Raster	70 Hz	Effective Display: A>5 x 5.25 B> 4.75 x 6
B 737-600/700/800/900	LCDs 5 across	8 x 8 ND, PFD, EICAS and MFD	Bitmap	60 Hz/20 Hz	
B 747-400	CRTs 5 across	8 x 8 ND, PFD, EICAS and MFD	Stroke & Raster	Refresh: 80/40 Hz Update: 20 Hz	6.4 x 6.4 effective display area
B 757/767	CRTs EADI over EHSI	EADI: A size (5.5 x 6) EHSI: B size (6 x 6.25)	Stroke & Raster	Refresh: 80/40 Hz (stroke/raster) Update: 20 Hz	A over B
B 777	LCDs 5 across	8 x 8 ND, PFD, EICAS and MFD	Bitmap	Refresh: 60 Hz Update: 20 Hz	6.4 x 6.4 effective display area
Fokker 70/100	CRTs 5 across	8 x 8 ND, PFD, EICAS and MFD	Stroke & Raster	Refresh: 80/40 Hz (stroke/raster) Update: 20 Hz	
MD-88/90	CRT	EADI & EHSI, both A size	Stroke & Raster	NA	
MD-11	CRTs 6 across	7.5 x 7.5 ND, PFD, EICAS and MFD	Stroke & Raster	NA	

Table 4-5 Display Capability – EFIS Equipped Aircraft

Non-EFIS aircraft may have displays on-board that are suitable for SVS applications. Most air transport aircraft are equipped with TCAS and some of those may have a display associated with this system. Weather radar displays are common in this category. EFIS equipped aircraft will typically integrate weather data onto the navigation or EHSI display. The HUD may turn out to be a cost-effective way to introduce SVS applications. This system enhances the operational capability of an aircraft while simplifying operations by integrating data into a single display. This last aspect of HUD is significant in that it alleviates many human factors issues that are typically associated with adding new displays in an already crowded cockpit.

Aircraft Type	Type & Configuration	Size (inches)	Capability	Refresh Rate/ Update Rate	General
TCAS display	Single LCD	4.5 x 4.5	Bitmap	Refresh 60 Hz Update 20 Hz	
Weather radar	Single CRT	5.5 x 5.5	Stroke 7 Raster	Refresh 70 Hz Update 20 Hz	
HUD	CRT projected	NA	Stroke		+/-15 deg. field of view

Table 4-6 Display Capability – Non-EFIS Equipped Aircraft

4.2.2 Characterization of Position Sensors

Position accuracy is most important to SVS application in that it allows the database to be presented to the pilot as accurately as possible. The accuracy levels are different for cruise, non-precision and precision approaches. In this section we take a look at the likely sensors to support SVS applications.

The FMS is the main source of providing position data. Traditionally the FMS blends a number of sensor inputs such as IRS, VOR, LORAN and DME and most recently GPS. The most accurate sensors are GPS and DME. In the US airspace there is sufficient DME coverage to provide position accuracy to less that 0.3 nm horizontally. Vertical accuracy will greatly depend on barometric altimeter. FMS with DME inputs with or without GPS should be sufficient to support most SVS application in cruise. Note that DME coverage in many parts of the world outside the US and Western Europe may not be sufficient to provide the accuracy advertised above.

GPS alone can provide even better accuracy. Selective availability results in a 100m error (2drms) horizontally and 156m error vertically (2♦). When WAAS becomes operational (end of 1999), the accuracy will drop to only a few meters. This should be sufficient for any non-precision approach SVS applications. Differential corrections from ground stations will reduce this to 1-2 meters and should be able to provide the accuracy necessary for precision approaches.

To properly drive SVS displays, one must also consider the availability and accuracy of parameters such as heading, pitch attitude, flight path angle and side slip angle. Typically these parameters are readily available. The required accuracy for these parameters needs to be defined.

4.2.3 Retrofit Issues

The displays being considered for SVS must be an improvement over the current EGPWS weather radar display. Section 2.6.8 identified typical aircraft display types and their appropriate use by the SVS applications. For example, the ND / MFD type of displays are typically used for strategic SVS applications while PFD / HUD types of displays are typically used for tactical SVS applications. Since strategic SVS applications fall into the essential category, retrofit of displays to support these applications will make certification relatively easy and less costly than strategic applications. Tactical SVS applications are critical in nature. The integration of these applications into existing cockpits may result in a difficult and costly certification effort. The Head Up Display (HUD) is one of the most promising add-on equipage options that may allow for the introduction of tactical SVS applications at a lower cost, since its installation does not impact the certification of the existing systems.

Retrofit issues are assessed using the same aircraft classification described in Section 4.2, i.e., aircraft are subdivided in three groups based on the available cockpit technology.

The ***first group*** of aircraft represents only 6% of the fleet and includes those aircraft with the most sophisticated display technology such as large CRT displays (majority in this group) and emerging LCDs. The retrofit issues for this group are complex. The graphic engines for most of the CRT equipped aircraft will not support 2-D or 3-D type of SVS applications while CRT displays may loose brightens as the displayed graphics increase. It is very likely that a display upgrade (to LCD) with a new graphics engine maybe the most cost-effective approach.

Side displays for strategic applications and HUDs for tactical applications are of course alternatives for these aircraft as well. All aircraft in this group are equipped with inertial systems. HUDs do not offer this group the operational benefits that they offer the other two groups. This mainly because aircraft in this group are already equipped with flight control systems with equal or better operational capability than a HUD can offer.

The ***second group*** of aircraft (approximately 28% of the fleet) is equipped with CRT displays that vary in size but have typically an effective display area that is less then 5.5 x 5.5 inches. Aircraft in this group have an EADI and EHSI. In many of these aircraft, the EHSI display is used to integrate weather radar and can display EGPWS data. The graphics engine capability of most displays in this group is limited. If the graphic needs for the SVS applications can be met by software upgrades (i.e., use existing graphics capability) then the introduction of such applications may be cost effective. One concern is the inability of CRT displays to meet brightness requirements when the number of graphic elements being displayed is increased.

If the graphics engine is to be upgraded or if the SVS application is graphic intensive, then it may be desirable to retrofit the existing displays with a newer technology, i.e., LCD, with improved graphics capability.

HUDs are also an attractive alternative for this group of aircraft as most aircraft in this group have inertial reference systems already installed. Side displays are also of interest assuming that the real estate in the cockpit can accommodate a new display.

The ***third group*** includes all aircraft that have electromechanical instruments. Approximately 66% of the commercial and business fleet belongs in this group. A significant number of these aircraft have weather radar displays so they can be retrofitted with EGPWS. Anything beyond this capability will require additional instrumentation. There are three likely retrofit options, 1) replacing electromechanical instruments with state-of-the-art LCD displays capable of including SVS applications, 2) adding a side display for strategic type of applications or 3) adding a HUD.

A HUD may be desirable as it significantly increases the aircraft's operational capabilities. The HUD option may be less desirable if an inertial system is not available on the aircraft. The addition of a side display is a relatively easy way to introduce strategic SVS applications into the cockpit. Space and ergonomic issues are the main concern.

In summary, it is not very likely that SVS applications providing additional benefits over EGPWS will be able to use existing display hardware. A HUD may be a cost effective alternative for aircraft equipped with an inertial reference system while side displays can only assist in strategic planning assuming the real-estate can be found. Strategic applications will be much easier to certify than tactical ones. Human factor issues and the criticality of the displays involved are the main reason why tactical applications will be costly to introduce.

Finally, the position sensor required to drive synthetic vision applications can be attained cost effectively using GPS / DGPS. An FMS with VOR / DME inputs may be suitable for strategic applications (enroute).

4.3 Key Aircraft Integration of Synthetic Vision System Issues

4.3.1 Display Issues

<u>Only 34% of the Fleet is EFIS Equipped</u>

- Most EFIS equipped aircraft only have limited graphics capability available
- Most graphics engines are only capable of the most elementary graphic elements
- Existing display size: Most displays may not be large enough for SVS applications
- Tactical applications are difficult to certify because tactical applications will affect the existing displays and drivers, which are certified to a critical level
- Upgrade to LCD may be necessary.
    - If the display graphics engine and / or display need to be upgraded it may be easier and less costly to upgrade to a new system with an LCD and improved graphics capability
- HUD and side displays may be alternatives for some aircraft

<u>66% of the Fleet Have Electromechanical Instruments</u>

- Old aircraft with electromechanical instruments cannot support SVS
- Require replacing electromechanical instruments with state-of-the-art LCD displays capable of including SVS applications
    - 5 ATI LCD instruments are a retrofit candidate
    - Redo of flight deck instrument panel to install new displays that have a different form factor than the old displays is a serious cost factor

4.3.2 Significant Aircraft Upgrades

<u>Incorporation of Tactical SVS Applications Will Require Significant Aircraft Upgrades</u>

- Capability of existing hardware is limited
- Existing displays and display drivers need to be modified
- HUDs may turn out to be a cost-effective way to introduce tactical SVS applications
    - HUDs enhance the operational capability
    - HUDs alleviate many human factors issues that are associated with adding new displays in an already crowded cockpit
    - HUDs may require less cockpit modification to install than new panel mounted displays

Incorporation of Strategic SVS Applications May Be Less Costly

- Strategic SVS applications fall into the essential category
- Retrofit of displays to support these applications may be less costly than strategic applications
- Side displays may be suitable for strategic applications

Incorporation of Tactical SVS Applications into A HUD

- May be more cost effective than display upgrades
- HUDs do not affect certification of existing aircraft equipment
- HUDs as add-ons do not affect operational procedures of existing systems which is significant training issue advantage
- However, HUDs requires an inertial reference system which many older aircraft do not have

4.3.3 Sensor Issues

Typically, sensor parameters such as heading, pitch attitude, flight path angle and side slip angle are readily available. However, the accuracy of these parameters need to be considered for SVS applications.

5.0 Liability and Certification Issues

The level of safety of a system and all its functions determines what the product liability and certification issues will be. At any particular period of time, the safety level of an aircraft and its systems may be defined in an absolute manner. However, the long-term desire of both the regulatory agencies and industry is to make the total aircraft as safe as possible. This is possible when changes in technology result in economic ways of providing safety improvements. The net result is that the ability of designers to produce safer aircraft does occur as technology advances are realized. In the area of Synthetic Vision Systems (SVS), the technology is now available to increase the pilot's situational awareness for the location of terrain, weather, traffic and obstacles along the intended flight path. The stand-alone SVS solutions for retrofitting existing aircraft may not be as economically feasible or provide all the capability desired when compared to new or retrofitted airframes with a complete suite of new technology of SVS compatible systems. However, there are retrofit approaches with minimal modifications that do provide economical solutions producing a measurable safety enhancement.

With the availability of a significant amount of new technology, the impression of much of the traveling public and even some flight crews is that new technology will produce systems where failures won't occur and accidents won't happen. The implication, then, is that designers of new technology systems and airframes are providing a maximum of protection against unexpected system operation so that safety is not impacted. This also implies that design implementations are completed to produce ideal human factors interfaces. Even with the most advanced technology it is not realistic to design a system that is 100% safe, irrespective of the level of investment. Figure 5-1 illustrates the basic safety trade-offs versus cost tradeoffs that must be made when a system is defined so that the finished aircraft is affordable to the users.

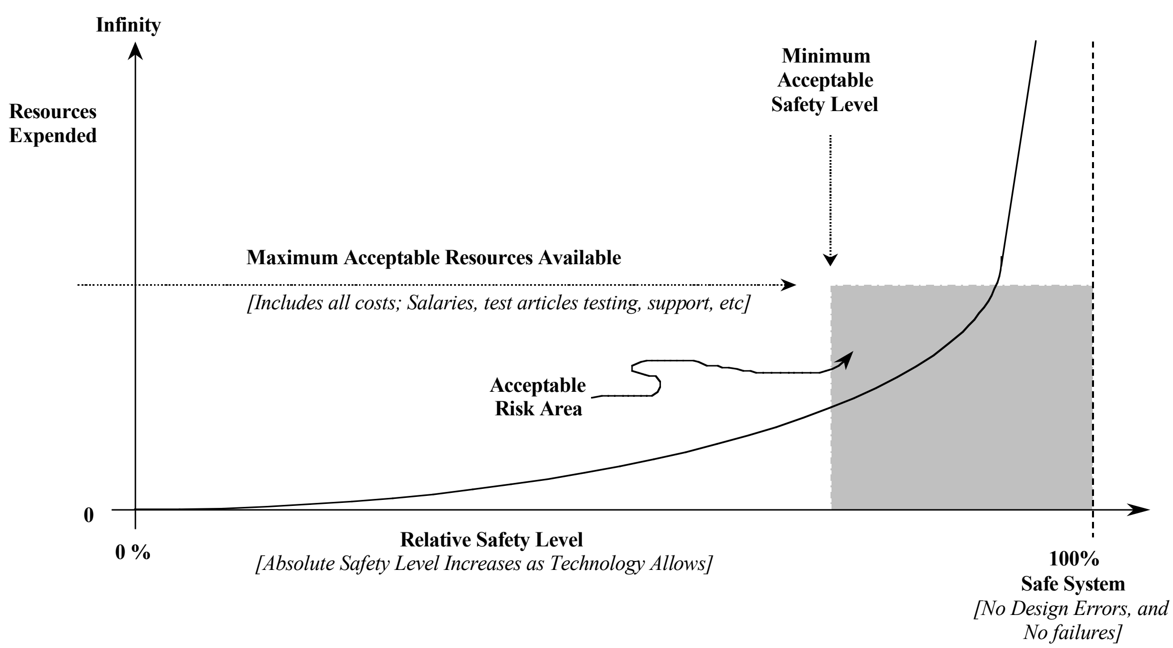

Figure 5-1 Safety versus Resources Required (Design Trade-Offs)

The design approach accepted by the regulatory agencies and the industry is to maintain the highest level of safety consistent with the capacity of the end user of the product to economically afford the completed product. With commercial aviation, this would be the ticket-paying passenger. For business and general aviation, this would be the organization or individual buying and operating the aircraft. The ability to measurably increase safety becomes increasingly more difficult as the systems become more complex and sophisticated. The intended operating environment and operational requirements of the system must be well understood and documented as a foundation for acceptably safe designs. Basic design concepts have to be put in place early in the development programs to provide simple and intuitive human interfaces with the aircraft and its systems. Today there is the advent of using terrain and obstacle data to provide such a safety improvement. As with all other aspects of aviation there are also risks that can be identified when new approaches are used. **The risks tend to be primarily financial risks. To get a new technology system like SVS certified is not as much of a risk as the risks associated with keeping the certification costs at levels that make the system economically viable in the marketplace.** Experience provides some background as to what the expected problem areas during certification are.

The greatest risk area in an SVS program is to get individual government and industry organizations to accept the liability associated with the databases used in SVS.

5.1 Certification Approach

Since the Federal Aviation Regulations (FARs) traditionally have been written around a single function in a specific system, it has been difficult to directly apply the rules to new technology systems coming on-line. There are provisions in the rules to allow for these types of certifications for “unique and novel” functions until specific requirements are put in place within the rules (At the present time, rulemaking is a lengthy process, i.e., 8 to 10 years). Use of “Special Conditions”, “Equivalent Safety Evaluations” and “proof-of-concept” methods are used to certify these new technology functions (systems). The problem is that these approaches tend to be cumbersome and they typically apply only to specific certification programs. Additionally, FAA approval of deviations and exceptions to specific performance requirements and regulations must be obtained. This in itself can have significant schedule and cost impact for a certification program.

The NASA AGATE program has addressed some of the issues for small, Part 23 aircraft, i.e., aircraft under 6000 pounds gross weight. Industry and FAA meetings have resulted in guidance material for safety [AC 23.1309-1C] and display [AC 23.1311-1A] requirements being revised based upon actual accident statistics for small aircraft. The resulting Advisory Circulars provide an improvement in total aircraft safety over existing aircraft by using new technology and operational concepts to enhance reliability of the hardware and ensure that fewer mistakes are made by the pilot. One of the problems encountered in the process of revising the guidance material was that since existing rules legally are the controlling requirement to show compliance for certification approvals, they limit how much advisory material may be used to modify the certification process now being used. This difficulty has fostered an AGATE desire to review the basic rules and initiate the rulemaking process to modernize the Parts 21 and 23 rules. It is anticipated that a similar situation will occur for other airworthiness parts, including Part 25, of the regulations.

The expected certification approach for SVS approvals will use the following process:

Initial Certification Approvals as used with TCAS

The Traffic and Collision Avoidance System (TCAS) approvals used algorithms defined by FAA subcontractors. The hardware implementation and coding of the supplied algorithms were left to the avionics equipment manufacturers. Specific functions of the TCAS system were evaluated on a test bench for generic performance. For the initial certification approval the performance of the whole system had to be demonstrated using two aircraft flying actual collision scenarios. Out of these tests a determination of what functions were generic and which were aircraft specific was made. For follow-on approvals only those functions that were determined to be aircraft specific had to be demonstrated with actual aircraft installations. When changes in the basic algorithms are modified, the approval again becomes an "initial approval" and specific tests have to be demonstrated on the bench and in the aircraft to show the system still conforms with the certification requirements. In a similar manner the SVS approval will be completed.

Basic Steps

a) Use existing regulatory requirements and advisory / guidance material as much as practical.

b) Get Technical Standard Orders (TSO) deviation approvals as necessary for those functions for which TSOs are applicable.

c) Use Conformity Inspections and Parts Manufacturing Approvals (PMA) for those functions that do not have applicable TSOs.

Likely Additional Steps

d) Use Special Conditions for functions that have little or no certification basis in the existing regulations (Special Conditions are negotiated between the applicant for certification and the FAA Certification Office to get agreement as to the issues and what an acceptable requirement would be).

e) Evaluate specific functions against similar functions previously certified to show that the new functions are at least at equivalent safety levels when compared to the approved function(s) (Equivalent Safety Evaluation).

Last Step Only if Needed

f) In some cases a specific function can be approved using a Proof-of-Concept approach. In some cases this is an economical approach for certification, but many times it requires extensive testing and analysis which are very costly.

Follow-on approvals as used with TCAS

When adequate documentation results from the initial certification so that the certification requirements are deemed to be covered, this documentation may be used as a basis for follow-on approvals. This approach simplifies approvals of new installations.

Long term

On the long term it is desirable to evaluate the applicability of existing airworthiness FARs, e.g., Parts 21, 23, 25, 27 and 29 to determine if rulemaking should be initiated to make the rules applicable to new technology functions, i.e., SVS.

5.2 Liability

Liability results to manufacturers, approving agencies, and operators of aircraft when designs are either deficient in safety characteristics, or are not produced and validated to acceptable safety criteria that exist at the time of the design, or when known existing safety problems are ignored for a product that is in service. Beyond this, more recent litigation has also focused on whether the manufacturer used "best industry practices" in the design and production of the item. That is, was it reasonable at the time a design was completed to have done a better job of anticipating design deficiencies? It is inherent in the aviation field that, by its nature, it is a relatively high-risk endeavor for any manufacturer of equipment or parts for an aircraft. This section will identify probable liability issues that may arise specifically as a result of using terrain and obstacle databases with Synthetic Vision Systems to improve operational safety as well as for normal navigation.

5.2.1 Identification of Liable Parties Issue

Since many of the organizations furnishing the databases are government organizations, it will be difficult to get them to accept liability for the data they are providing. A similar case occurred with the Traffic Collision and Avoidance System (TCAS) algorithms. The FAA furnished the basic algorithms to industry. These algorithms had to be implemented in hardware and software by the manufacturers of the TCAS in the precise manner defined by the FAA. The FAA could not accept liability for the quality of the algorithms. It was then necessary to have the originators of the algorithms agree to accept all or part of this liability. It is expected that the liability associated with the terrain and obstacle databases will be a mixed bag. Some government agencies are already providing similar data to users. They may be willing to accept the liability for the accuracy of the database in the format in which they are handling it. Obviously, each processor of the data will have to accept some level of liability for the function(s) and processes they perform. **This will likely be the major issue in developing a viable SVS.**

5.2.2 Database Accuracy Identification Issue

Ideally a database should carry an identifier with it that defines the accuracy of the specific data in the database to the user systems. One can conceive typical scenarios where almost identical operational situations occur in different geographical locations where the terrain and obstacle data may have different accuracy levels. This is particularly true when one aircraft is being operated in different geographical areas throughout the world. CONUS data is perceived to have more inherent accuracy than data gathered in the rest of the world. The next level of accuracy is probably Western Europe and Japan. After that the accuracy of the database can be very unreliable. Since much of the data is furnished by government agencies in specific countries, these agencies may be unable or unwilling to provide precise accuracy measurement values for their data.

Obstacle data presents a unique challenge. The natural topography of the earth remains somewhat constant. Foliage growth and long-term terrain shift changes, i.e., moving a mountain, may occur, but they are not very relevant on a dynamic basis. The accuracy of the terrain contained in a specific database is the important parameter. This is not the case with obstacle databases. Since obstacles are man-made, a particular obstacle can change dramatically overnight. A complicating factor for collecting and maintaining obstacle data is that survey and measurement methods tend to be costly. To get accurate obstacle data is a time consuming, on going and a high cost task.

The concern is that simple acceptance of these risks will not be adequate to cover the necessary liability exposure when using terrain and obstacle databases in an SVS. Such an approach would certainly not satisfy the best industry practices criteria since some action needs to be demonstrated that continuing and updating measurements are being made to detect changes in a given databases. Additionally, it must be shown that this information is being routinely distributed to the end users in a timely manner.

The alternatives may include one or more of the following:

- System designs need to provide adequate buffering of the data to ensure that the worst case errors will not result in inadequate terrain or obstacle clearance. The obvious concern with this approach is that a useful operational scenario may not be available because of the low precision in the supplied terrain and obstacle data.
- Persuade as many data furnishing organizations as possible to provide defined accuracy values in the basic database. This would allow the systems to use appropriate dynamic accuracy buffers added to the supplied data consistent with the database being used. Once again this approach may not provide a useful operational system.
- The most desirable alternative is to set up an independent terrain and obstacle data measuring and database maintenance organization. The obvious problems with this approach are that there are considerable financial and political issues that make it difficult and perhaps unlikely to succeed.

5.2.3 Database Accuracy Issue

As discussed in other parts of this study, the data used to provide terrain and obstacle information is derived from a number of sources. These data sources range all the way from providers of the data with well defined accuracy levels to those who supply data with unknown accuracy levels. Various organizations that compile and process these databases use a number of methods and processes to validate the sources of the data and to verify that it is not corrupted in any manner as a function of the processing steps. It is extremely difficult with existing terrain and obstacle databases to provide an end-to-end validity value or error margin for the resultant database. In addition, the end users are likely to be expecting more precision than may be possible with the databases that are available today. Without some resolution of this issue, the operational value of an SVS may be reduced below useful levels.

5.3 Certification

5.3.1 Certification Criteria Issue

The FAA presently doesn't have specific criteria in place to approve, or certify systems containing, terrain and obstacle databases. The present approvals of navigation databases in terms of accuracy and quality control of the products are generally left to the suppliers of the databases, pending the publication of new guidance material such as RTCA DO-200A. The FAA approach seems to be to use vendor specific reviews versus formal approvals. This does not lead to a standard set of approval criteria. There are attempts to standardize some procedures in the processes with RTCA Documents DO-200A and DO-201A. These documents are not complete enough as presently written to establish end-to-end accuracy requirements, data processing and assembling criteria, quality control standards or approval methods. This issue may be mitigated by discussing what the criteria will be with the FAA. Typically this kind of issue is resolved when the first certification is requested. The primary concern is that the cost of this activity must be acceptable.

5.3.2 Level of Demonstration for FAA Approval Issue

There is no FAA organization set up to handle database approvals. Therefore, approvals would likely be by special conditions, equivalent safety evaluations or proof-of-concept demonstration. At the present time there are some special approvals for similar systems to SVS being handled on an operational basis by FAA's Flight Standards organization (Juneau Alaska approaches; Vail, Colorado departures and some Northwestern US tracks and approaches). Without the certification criteria being in place, FAA approvals may be very extensive and inconsistent across FAA regional Aircraft Certification Offices (ACO). It is anticipated that an approval could require a large number of demonstration flights in a cross section of geographical areas to provide a basis for validating database accuracy, system operation, dependence of installation on aircraft type and pilot usability. This issue will have to be negotiated with adequate technical substantiation with the specific FAA approval organization.

5.3.3 Variable Operational Approval as Function of Flight Regime Issue

There are no established FAA requirements concerning how the SVS would be approved for specific operations throughout the aircraft flight regime. This could include the possibility of approving the system to use different error budgets when in specific flight and weather conditions, e.g., in the terminal area, enroute or on approach in IFR weather. Operation of the SVS under failure conditions would need to be considered when this operational approval is defined.

5.3.4 Operational Training Issue

In addition to the certification demonstration approvals, there is some precedent to have the operator complete specific training and demonstrate proficiency when using the SVS. Recurrent operational proficiency requirements could be incorporated in instrument proficiency requirements. Whether this would require an entry on the operational license of the pilot needs to be determined. To some extent the level of initial and recurrent requirements would depend upon how operationally intuitive the SVS is to use. In any case, it if vital that this training be conducted in a cost effective manner.

5.3.5 Software Loading Issue

Activities are being taken to define how software (containing databases) may be approved to be loaded into aircraft systems in the field. To date the problem deals not with the content or quality of the software, but how it is identified and controlled during the distribution and loading process. There have been some specific processes used and approved by the FAA on a case-to-case basis to allow this field loading of software. A definitive process is yet to be defined. The specific concerns are:

- What is the approval process for any software distributed to the field to be loaded onto an aircraft? This includes knowing the correct software is being provided in the distribution media and what authorities approved it at the supplier's and user's facilities.
- What control is provided to ensure that the software (database) is the correct software for a specific aircraft configuration it will be loaded into?
- How does the person loading the database package verify that the "load" took place correctly?
- If the database load occurs in a unit outside the aircraft, how is the unit identified which contains the correct software for a specific aircraft type or operational mission?
- How does the pilot determine that the database expected to be in the aircraft is indeed loaded and is the correct version?

5.3.6 Approval Criteria for End-to-End Validation and Verification Issue

A concern in quality of data in a database involves how the data is processed from end-to-end. As the databases exist today, there is a level of interpretation involved in each step of the processing and assembling of the final data package. This results in the need for additional ad-hoc test processes to cross check databases to validate correctness, determine the availability of data needed to perform a particular function, e.g., approach vs departure, and lack of a defined and controlled process for end-to-end control.

RTCA Document DO-200A as presently drafted provides guidance to define the kinds of processes needed to provide end-to-end control of a database. A summary is provided below.

- Document DO-200A provides the <u>minimum standards for the processing</u> of aeronautical data.
- The quality of the data is its ability to satisfy the requirements for its safe application in the end system.
- The quality of the database is characterized by it's accuracy, resolution, assurance level, traceability, timeliness, completeness and format.

<u>Assignment of required numeric values for data quality characteristics must take into consideration potential causes of failure, risk identified as failures per flight hour, and potential impact to safe flight as a result of failure. This data quality would be expected to vary as a function of the geographic region and source data quality processing.</u>

- Aeronautical Chain – a conceptual representation of the path data takes from its creation to its end user. Each link provides functions such as: originating, transmitting, processing, application integration and end use.
- Processing of aeronautical data includes receiving, assembling and translating, selecting, formatting and distributing.

- Data shall have agreed upon data quality characteristics. The user of the data is responsible for establishing the actual data quality characteristics.
- Data Processing Procedures shall establish the means by which data quality requirements are met when data is received and processed.
- Data Configuration Management shall ensure that configuration controls have been implemented to provide assurance that the aeronautical data produced is correctly identified for a declared period of validity and that all data requirements as well as any detected errors have traceability.
- When required, software tools shall be qualified to demonstrate that the tool complies with the intended user's data requirements.
- Any participant in the aeronautical data chain claiming compliance to established requirements must be able to demonstrate compliance. An audit shall confirm that there are plans, controls and procedures in place and being adhered to in order to assure the required quality levels of the aeronautical data is met.

There is concern that DO-200A and its companion document DO-201A will not provide practical end-to-end control over the database product from the terrain and obstacle data measurement through the processing to use by an end user. The philosophy used is based on similar regulatory approaches where each part of the approval process is essentially certified to be correct. In those cases there is better FAA oversight of each step in the process. In the terrain and obstacle database situation the end user may not be able to rely on the quality assurance that takes place during each step of the collection, processing, assembling and other processes in the chain without better oversight of each process step.

5.3.7 Limitations For Common Function Hardware and Software Issue

It is very desirable to reuse as much of the existing installation or new SVS hardware and software whether the installation is a retrofit of an existing installation, modification of an existing installation or a completely new installation. Since the majority of possible users at this time are aircraft equipped with electromechanical display systems, this creates significant trade-offs that must be made. To provide the optimum configuration for each aircraft that could have a combination of modified systems to implement SVS and / or add-on or completely new SVS systems installed will be difficult. In many cases it will be impractical to find adequate space in the cockpits for add-on and replacement hardware.

When it is possible to modify existing hardware and software to accommodate some level of SVS capability, limitations present themselves in the form of such areas as the brightness range of existing CRT and LCD display media. It is difficult to get adequate display brightness range to meet certification criteria with some existing displays. SVS functions require a significant increase of data handling throughput time to present a useful amount of display symbology. This affects the display data refresh rate and the brightness of the display. The implication then is that for some installations displaying an amount of SVS symbology that provides a beneficial improvement of operation may not be feasible without changing out the existing displays and graphics engines in the hardware that drive the displays.

A second related issue concerns the economical reuse of various SVS hardware and software components throughout various installations. Depending on the application, the SVS display information will be considered essential or critical for certification approval. With integrated avionics systems this could lead to having SVS software and / or hardware common with other avionics functions which are certified to a different level of criticality. If this occurs, it will lead to increased development and certification costs to qualify all the software and hardware to critical levels. There are design approaches that mitigate these kinds of problems, but the processes to do this must be implemented as requirements before the designs are started.

5.3.8 Human Factors Evaluation Criteria Issue

It has been determined by review of records that a significant cause of accidents is either directly attributable to the pilot or to the pilot has takening incorrect actions that leads to a chain of events that results in an accident. The NASA AGATE program has taken an approach for small Part 23 aircraft to develop new systems that have human factors criteria defined into the design requirements. The FAA is now requiring human factors evaluation on all certifications. The problem is that this criterion is not well defined or consistently applied. It therefore becomes a very subjective determination as to whether a specific installation meets the human factors requirements for certification. In military human factors evaluations this criterion has been defined, but it is not a very cost-effective approach. Efforts are presently under way by industry and the FAA to provide human factors certification criteria, but progress is slow. This has caused excessive system redesign and schedule delays on certifications.

5.3.9 Acceptance by Other World Regulatory Agencies Issue

There is no evidence that the European Joint Airworthiness Authorities (JAA) or other world regulatory agencies are willing to accept any FAA approvals or that they have criteria and processes in place to provide avenues for their own approvals. It would be very desirable to sell and operate these products worldwide and have FAA approvals accepted under bilateral agreements with other governments as well as have other national approvals accepted by the FAA. The Canadian regulatory agencies are particularly critical of some FAA approvals of this type at the present time. They will not accept some of them without additional testing and evaluation.

5.4 Key Certification and Liability Issues

5.4.1 SVS Certification Issues

- Currently there are no standards defined for certifying SVS applications
  - No cognizant FAA organization has defined
  - Testing and level of demonstration required for certification may be overkill
  - Approvals will likely require use of equivalent safety
    - TSO deviations will need to be requested
    - Exceptions to rules may need to be approved
    - Rule making effort may be required (may take 8 to 10 years to complete)
- Need an approval criteria for end-to-end verification and validation
  - DO-200( ) and DO-201( ) being defined to provide validation and verification plus quality assurance
  - Not obvious that these documents provide adequate assurance of the quality of the data

- Limitations for common function hardware and software
  - Brightness range of displays; particularly for retrofit installs
  - Criticality of common hardware and software for multiple functions
- FAA objective human factors evaluation are criteria not in place
- FAA approval acceptance by other world regulatory agencies
  - FAA and JAA have been harmonizing FARs And JARs
  - Other world agencies approvals are a concern

5.4.2 SVS Liability Issues

- Identification of liability parties
  - As with TCAS approvals, the problem is to identify liability of participating parties
- Multiple parties are involved
  - Data source providers
  - Value added providers who integrated multiple data sources
  - Avionics manufactures and integrators
  - End users: airlines and pilots
    - Improper database updates
    - Unintended operational use of database information
- Need to get each participating party to accept appropriate level of liability

6.0 Summary and Recommendations

In this task contract, the Rockwell Collins, Embry Riddle Aeronautical University and Jeppesen research team investigated the application of Synthetic Vision to achieve improved safety and increases in operational benefits. In doing so, accident safety factors were examined to determine how Synthetic Vision can eliminate or reduce accident causal factors. The various flight phases were studied to determine how Synthetic Vision might extend current operations to provide benefits.

A generic synthetic vision system concept was used to identify top-level requirements for the various synthetic vision sub-systems and to identify key issues associated with the technology. A set of candidate synthetic vision system (SVS) applications were identified and categorized as safety systems, strategic or tactical systems. Major points of emphasis for the study were 1) the databases needed to support these synthetic vision applications, 2) aircraft retrofit of synthetic vision sub-systems, especially the flight deck displays, and 3) a review of certification and liability associated with the use of Synthetic Vision in the flight deck.

Numerous issues were identified and categorized in each section of the report. The major issues are collected in the report Executive Summary and are not repeated here. However, the two major issues identified in this study are 1) the lack of available high-integrity SVS databases and 2) the difficult retrofit problem in integrating future SVS applications into the current aircraft fleet.

This study can serve as a starting point to address specific research topics, such as:

7) Refine the operational concept for specific SVS applications that offer the greatest potential benefits
    - Refine database accuracy, resolution and integrity requirements for these applications.
8) Resolve the numerous database related issues, especially those related to "database process" and "database integrity"
    - Develop an industry standard on how to achieve a certifiable, high-integrity SVS database
    - Develop an industry standard process for the handling and processing of SVS databases from data source provider to SVS end user
    - Note: A consortium of US government data mapping agencies, FAA, and industry is likely required to provide high-integrity SVS databases.
9) Develop a synthetic vision applications roadmap and strategy for incremental retrofit to the existing fleet.
10) Develop certification standards for Synthetic Vision.
11) Conduct human factors studies to determine the appropriate type of information, information formats, and information presentation on synthetic vision displays.
12) Develop companion graphics generation capabilities for appropriate types of displays to support the display concepts that result from human factors investigation.

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8.0 Acronyms and Abbreviations

2-D	Two Dimensional
3-D	Three Dimensional
AC	Advisory Circular
ADI	Attitude Direction Indicator
ADRG	Arc Digitized Raster Graphics
ADS	Automated Digitizing System
ADS-A	Automatic Dependent Surveillance-Addressed
ADS-B	Automatic Dependent Surveillance-Broadcast
AGATE	Advanced General Aviation Technology Experiment
AIP	Aviation Information Publication
AMASS	Airport Movement Area Safety System
ANP	Actual Navigation Performance
AOC	Airline Operational Communications
ARINC	Aeronautical Radio, Incorporated
ASD	Airport Survey Data
ASI	Italian Space Agency
ASMD	Airport Safety Model Data
ASMD	Airport Safety Modeling Data
ATC	Air Traffic Control
ATI	Instrument Size Unit of Measurement
ATN	Aeronautical Telecommunications Network
AWIN	Aviation Weather Information
BIL	File Format
BIP	File Format
BSQ	File Format
CAA	Civil Aviation Authority
Cat III	Precision Landing System Operational Performance Category
CDTI	Cockpit Display of Traffic Information
CFIT	Controlled Flight Into Terrain
CLL	Center Line Lighting
CNS	Communication, Navigation, and Surveillance
CONUS	Contiguous United States
CPDLC	Controller-Pilot Data Link Communications
CPU	Central Processing Unit
CRC	(1) Cyclic Redundancy Check
	(2) Cyclic Redundancy Code
CRT	Cathode Ray Tube
dBASE	File Format
DCW	Digital Chart of the World
DCW	Digital Charts of the World
deg	Degree
DEM	Digital Elevation Model
DFAD	Digital Feature Analysis Data
DFAD	Digital Feature Analysis Data
DFAD	Digital Feature Analysis Data
DGPS	Differential GPS
DH	Decision Height
DIA	Denver International Airport

DIME	Dual Independent Map Encoding
DLG	Digital Line Graph
DLR	German Aerospace Center
DMA	Defense Mapping Agency
DME	Distance Measuring Equipment
DOD	Department of Defense
DOD	Digital Obstacle Data
DOQ	Digital Ortho Quad
DTCC	Datum Transformation Coordinate Conversion
DTED	Digital Terrain Elevation Data
DTED	Digital Terrain Elevation Data
DTED	Digital Terrain Elevation Data
DVOF	Digital Vertical Obstruction File
DXF	AutoCad Drawing File Format
EADI	Electronic Attitude Director Indicator
EAS	(AlliedSignal) Electronic & Avionics Systems
EFIS	Electronic Flight Instrument System
EGPWS	Enhanced Ground Proximity Warning System
EHSI	Electronic Horizontal Situation Indicator
ERAU	Embry Riddle Aeronautical University
ESAS	Enhanced Situational Awareness System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FAS	Final Approach Segment
FFD	Fast Flash Disk
FIS	Flight Information System
FMS	Flight Management System
FTP	File Transfer Protocol
GA	General Aviation
GCAS	Ground Collision Avoidance Systems
GCP	Ground Control Points
Gen Av	General Aviation
GeoTIFF	File Format
GIS	Geographic Information System
GLS	GPS Landing System
GNSS	Global Navigational Satellite System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GRASS	Geographical Resource Analysis Support System
HDD	Head-Down Displays
HLOD	High Level of Detial
HUD	Heads-Up Display
Hz	Hertz (cycles per second)
IAP	Instrument Approach Procedures
ICAO	International Civil Aviation Organization
ID	Identified
IFR	Instrument Flight Rules
IGDS	Interactive Graphic Design Software
IGES	Initial Graphics Exchange Standard
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions

ITD	Interim Terrain Data
ITD	Interim Terrain Data
JAA	Joint Airworthiness Authorities
JFIF	JPEG File Format
JPEG	File Format
JPL	Jet Propulsion Laboratory
LAAS	Local Area Augmentation System
LCD	Liquid Crystal Display
LLOD	Low Level of Detail
LOC	Localizer
LOD	Levels-Of-Detail
LORAN	Long Range Navigation System
MAP	Missed Approach Procedure
METAR	Meteorological Aerodrome Report
MFD	Multifunction Display
MIADS	Map Information Assembly Display System
MLOD	Medium Level of Detail
MLS	Microwave Landing System
MSAW	Minimum Safe Altitude Warning
MSL	Mean Sea Level
NA	Not Available
NASA	National Aeronautics and Space Administration
Nav	Navigation
ND	Navigation Display
NDB	Non-Directional Radio Beacon
NGS	National Geodetic Survey
NIMA	National Imagery and Mapping Agency
NM	Nautical Mile
nmi	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NOS	National Oceanic Service
NOTAM	Notice To Airmen
NPA	Non-Precision Approaches
ONC	Operational Navigational Charts
PA	Precision Approaches
PAL	Precision Approach and Landing
PFD	Primary Flight Display
PIREPS	Pilot Reports
PMA	Parts Manufacturing Approvals
RGB	Red / Green / Blue
RLC	Run-Length Compressed
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RVR	Runway Visual Range
RVSM	Reduced Vertical Separation Minima
SAAP	Single Aircraft Accident Prevention
SARPS	Standards and Recommended Practices
SDTS	Spatial Data Transfer Standard
SHRM	Standard Vertical and Horizontal Recovery Maneuvers
SLF	Standard Linear Format
SPIFR	single Pilot Instrument Flight Rules

SRTM	Shuttle Radar Topography Mission
STARS	Standard Terminal Arrival Routs
STDS	Spatial Data Transfer Standard
STMS	Shuttle Topographic Mapping Survey
SUA	Special Use Airspace
SVRM	Standard Vertical Recovery Maneuver
SVS	Synthetic Vision System
TASS	Terrain Awareness Safety System
TAWS	Terrain Awareness Warning System
TBD	To Be Determined
TCAS	Traffic Alert Collision Avoidance System
TERPS	Terminal Instrument Procedures
TFW	File Format
TIFF	File Format
TIN	Triangular Irregular Networks
TIGER	Topologically Integrated Geographic Encoded Referencing
TIS	Traffic Information Services
TIS-B	Traffic Information Services – Broadcast
TSE	Total System Error
TSO	Technical Standard Orders
TSPS	Terrain Strategic Planning System
UK	United Kingdom
US	United States
USGS	US Geological Survey
USIGS	US Imagery and Geospatial Information System
VFR	Visual Flight Rules
VOR	VHF Omnidirectional Radio
VPF	Vector Product Format
VPF	Vector Product Format
WAAS	Wide Area Augmentation System
WGS	World Geodetic System
WXR	Weather Radar System

Appendix A Synthetic Vision Study Review of Literature

A-1 Introduction

A-1.1 Cockpit Display Technology

Today, electronic displays have replaced the older mechanical instruments. Some of the older instruments have not been eliminated but are delegated as backups in case of primary flight instrument failure. Display technology and computer systems have become key elements in most recent generations of aircraft. Current onboard systems can now control the aircraft from brake release through climb, cruise, and landing (Abbott et al. 1993). Wiener (as cited in Abbott, et al. 1993) simply defines automation as replacing the human function with machine function. In the case of cockpit automation, it would be more appropriate to replace the term machine with computer.

Some of the advanced technology systems presently in use include electronic flight information systems (EFIS), flight management systems (FMS), as well as various systems which include recent technological advances such as the collision avoidance system (TCAS), terrain awareness and warning system (TAWS), head up display (HUD), and automation systems that provide the aviation industry the opportunity for safer and more efficient transportation. More recently, a terrain avoidance system was developed called the Enhanced Ground Proximity Warning System (EGPWS). EGPWS uses global positioning systems and an on-board global terrain database, which provides pilots with a graphic picture of the terrain in front of them. EGPWS provides up to 60 seconds of advanced audio warning in the event that an aircraft is on a collision course with terrain. In 1998, the Federal Aviation Administration (FAA) announced safety regulations requiring passenger aircraft to be equipped with enhanced systems such as EGPWS to prevent controlled flight into terrain (CFIT). General Aviation (GA) aircraft, however, are not required to have such a device, even though CFIT is one of the leading causes of GA aircraft accidents. The National Transportation Safety Board recognizes this as a major safety problem in corporate and air-carrier flight operations as well.

The majority of CFIT accidents can be attributed to the loss of situation awareness (e.g., pilot's inability to stay ahead of the airplane). A common occurrence is that of a low skilled, non-instrument rated pilot, flying into marginal weather (e.g., VFR into IFR). Unable to maintain situation awareness in the IFR conditions typically leads the unaware pilot directly into terrain with little or no warning. Although accidents of this type have occurred primarily in general aviation operations, air-carrier and corporate aircraft have also crashed due to the lack of situational awareness of the flight crew. For example, in 1995, American Airlines Flight 965, a Boeing 757, crashed while in controlled flight on approach to Cali, Columbia. The event occurred during clear weather night operations. Loss of situation awareness was cited as a contributing cause of the crash. Although the 757 was equipped with a mandatory GPWS, the GPWS did not provide the warning in time for the crew to successfully avoid the mountainous terrain. The FAA cited the Cali accident as evidence "that there is a need for regulations that require enhanced systems on commercial aircraft" (FAA, NPRM). The technology is available which enables aircraft to warn the pilot of impending terrain and obstacles. The need for technology that will allow pilots to see potential conflicts during low visibility, using cockpit instrumentation only, has never been more apparent.

A-1.2 Synthetic Vision

The next logical step in the progression of terrain avoidance technology is that of Synthetic Vision. Enhanced Vision (EV) or Synthetic Vision is a generic term referring to any technique where human vision is somehow enhanced. Ahumada, Foyle, Laimer, and Sweet (1992) defined Enhanced / Synthetic Vision as terms used to describe a group of advanced technology systems that will present or augment out-the-window information.

Near-term designs which are termed by NASA as Enhanced Vision Systems (EVS), are such systems as sensor imagery with superimposed flight symbology on a (HUD), and may include such enhancements as runway outlines, obstacles, taxiways, and flight corridors. NASA calls the longer-term designs Synthetic Vision Systems (SVS), which may be capable of allowing pilot's to fly with a real world representation displayed in the cockpit. Information that may not otherwise be seen, such as the runway in bad weather, would appear in 3-D format in the aircraft cockpit.

The term "synthetic vision" probably originated in aviation, where the current goal of synthetic vision is to allow the pilot to perceive the environment ahead of the aircraft. The long-term goal of Synthetic Vision Systems (SVS) is to have a fully automated aircraft from departure taxi, through takeoff, landing, and arrival-taxi; all being accomplished solely by onboard sensors and processing systems. The goal of aviation companies (e.g. general aviation, corporate aviation, and air-carrier aviation) is to eliminate costly training expenses, operational inefficiencies, thus, increasing situational awareness and the margin of safety.

Another goal of Synthetic Vision technology is to provide all weather flying capabilities for novice and expert pilots, which will improve safety across the entire spectrum of aircraft types and pilots; eventually accomplishing all these goals without a forward looking window in the aircraft cockpit.

NASA completed "Synthetic Vision" flight- tests on a NASA 737 research aircraft over a three-month period ending in 1996. "Researchers are hoping that by enhancing the pilots' vision with high-resolution video displays, aircraft designers of the future can do away with the expensive, mechanical devices such as the drooping nose of early supersonic transports. Forward-looking windows would be eliminated, making way for large-format displays filled with high-resolution images and computer graphics" (Henry, & Nolan-Proxmine, 1996).

A-1.3 Human Factors

The continued development of improved, more reliable automated systems is paramount in the quest for industry acceptance of high-technology, and eventually a completely automated aircraft. The rapid changes in technology must be accompanied by rapid changes in pilot training. "Not only does cockpit automation change the pilots' roll from active participant to passive observer, automation causes a resultant increase of the pilots' boredom, complacency and perceived degradation of flying skills" (Wiener & Curry, as cited in Abbott, et al.).

Automation induced operational errors have been attributed to several air-carrier and corporate aircraft accidents. Much of the safety derived from using enhanced visual systems depends primarily on the interface between the computer technology, and the human element (e.g. pilot, programmer, and maintenance technician). Eliminating what the FAA termed as "automation surprises", where the pilot or flight crew doesn't understand or expect the behavior of the automation, is a major task for those involved with the research and design of future automation technology. Flightcrews are often faced with trying to answer the commonly asked questions about automation behavior, “Why did it do that?” “What is it doing now?” and “What will it do next?” Automation surprises such as these occur at all levels of the pilot hierarchy—from novice to expert, and at all levels of aircraft performance--from single engine propeller, to multi-engine jet. “Complex automation interfaces, large differences in automation philosophy and implementation among different airplane types (including different airplane types from the same manufacturer as well as from different manufacturers), and inadequate training also contribute to deficiencies in flightcrew understanding of automation” (FAA, NPRM, 1997).

Human-centered automation addresses the need for the automation to fit human physiological and psychological requirements. In FAA NPRM (1997), the FAA’s Human Factors team related concern about the quality and the quantity of automation training flightcrew's receive. Stated objectives by this team which, if analyzed and researched carefully, can be used to prevent the design problems related to interfaces, specific and generic training qualification and operational problems related to pilot / airplane interfaces. In Abbott et al., (1994) it was stated that “previously, the relevant human factor requirements were not considered from the initial design stage. This led to a myriad of human factor problems that warranted attention. Anthropometric requirements, complacency, vigilance issues, boredom, system complexity, and situational awareness are examples of factors that were not considered fully in the early stages of the automation revolution.”

A-2 Display Issues

What the pilot sees out-the-window correlates directly with the production of new technologies in Synthetic Vision. The analysis of visual cues and visual limitations are at the forefront of Synthetic Vision research. Displaying visual cues that preserve the most useful and unambiguous cues pilots naturally see is one of the challenges that face human factors / engineering researchers and designers. Foyle, Kaiser, and Johnson (1992) said that visual cues may not necessarily be intuitive and immediately comprehended. Instead, they require training to use, and even more importantly, from a safety view, may be used incorrectly in the early stages of training. At the present time augmentation of visual cues may be done, but in limited fashion, through Head-Up-Display (HUD) symbology. Enhanced / Synthetic Vision Systems will allow a more natural representation of out-the-window scenery.

In a study by Foyle, Brickner, Sanford and Staveland (as cited in Foyle, et al.), the recognition of objects in general is greatly affected by the type of imagery viewed. Non-terrain objects were recognized faster with Infra-red (IR) imagery than when viewed with regular television technology. The terrain targets, however, were recognized faster with television. Under IR imagery, the terrain targets did not appear as expected, thus introducing cognitive factors into terrain recognition. Cognitive factors such as visual fatigue, divided attention, and mental confusion can occur. The differences between the appearance of IR imagery and direct vision or TV may impact the use of Enhanced / Synthetic Vision Systems. For example, the visual cues in runways may either be augmented or degraded depending on environmental conditions and material makeup. Depending on the thermal history, and the emissive and reflective properties, runway paint markings may not be accurately depicted by an IR sensor. Other runway characteristics such as cracks, and holes, might dominate the display in IR vision systems, further increasing the cognitive workload.

To counter visualization concerns, a technique called Selective Dynamic Manipulation (SDM) presented by Chuah, Kolojejchick, Mattis, & Roth of Carnegie Mellon University, has been designed. "Selective Dynamic Manipulation is a set of interactive techniques for 2-D and 3-D visualizations. The structure of SDM components is broken down into three primary interactive techniques: (1) Method of selection, which provides a high degree of user control; (2) Interactive operations, which calls for dynamic, real-time interactions; and (3) The feedback mechanisms and constraints placed on the behavior and appearance of objects" (Chuah, et al.) SDM supports a variety of techniques which users can combine to solve a wide variety of problems. Currently, isolated problem solving seems to be the norm in interactive techniques. The goal of SDM is to provide the user with a wide variety of problem solving techniques. For example, static displays are limited in their ability to clearly represent large blocks of data. Due to this, and the limited amount of the available information space on displays, clutter and / or object occlusion masks the detail needed to interpret the given data effectively. SDM will allow the user an option to change the scale in order to keep it in context with the environment. Color, height, contrast, size, and visibility are just a few of the data sets that can be manipulated by the user.

At Wright-Patterson Air Force Base, Ohio, research is also being conducted in display technology, more specifically, the Panoramic Cockpit Control and Display System (PCCADS) which uses computer-generated graphics to replace dials and gauges in the fighter cockpit, with one screen. Current style Cathode Ray Tube (CRT) displays can be represented on the screen. Reconfiguring the cockpit display in flight, touch-sensitive screens, voice commands, moving cursor operated by head-mounted tracker, and the ability to incorporate a head-up display (HUD), are some of its capabilities.

Another cockpit simulator at Wright-Patterson is called MAGIC (Microcomputer Application of Graphics and Interactive Communication), which is looking into future cockpit views of pilot's surroundings. It appears from the available research information that Wright-Patterson has available, advancing cockpit / design issues, especially in the areas of human engineering and interface design is a high priority issue.

There is an increased reliance on Liquid Crystal Displays (LCD) and Cathode Ray Tube Displays (CRT) with their many variations in color, and symbology. Hundreds of different colors and hues can be used, along with an infinite number of sizes and shapes. According to Fischer, Haines & Price (as cited in Ahumada, et al.), "superimposed symbology, whether on a HUD or HMD, under certain conditions, has been demonstrated to lead to visual and attentional fixation." Under visual fixation, pilots are less likely to process other symbology information, and / or the world seen through the HUD, or imagery presented on the HUD. The pilot's eyes can become fatigued, thus raising the visual sensitivity threshold, degrading visual acuity. Because of these and other limitations, research related to Synthetic Vision Systems has shown a trend towards enhancing the out-the-window display imagery, in effect, decreasing visual fatigue. By doing this, necessary visual cues limited by degraded operating conditions are put back to the scene. Fixation and fatigue caused by searching for terrain, aircraft, or the runway environment can be eliminated with precise out-the-window graphical displays.

With the advent of 3-D navigational database maps and cartographic displays this is possible. The representation of three dimensions on 2-D displays can be achieved using these three methods: (1) Pseudo-perspective displays use graphical techniques such as shadows, perspectives, or hidden lines to create the appearance of three dimensions. The creation of 3-D impression is solely dependent upon the map-reader's perceptual ability for abstraction. The enhanced visual stimulation caused by a 3-D effect will be diminished if the reader's ability is limited. (2) Stereographic (or stereoptic) displays provide a separate picture for each eye. Real 3-D objects produce the same visual stimuli that stereographic displays produce. Thus, the need for intentional mental abstraction, which increases pilot workload, is avoided. Stereoptic displays have an effective depth of a few feet. Distance and angle must be precisely kept in order to allow for the creation of mental 3-D pictures. This research is very important to the design of new displays, because it shows that proper angles used in displays can maximize the potential of current and future displays. In addition, without them, a pilot using a display set at improper angles won’t be able to correctly judge relative distance between his aircraft and others around him. (3) Holographic displays, which are the most complex technology in cockpit displays, require the least amount of mental abstraction, thus, causing the least amount of visual fatigue. Again, like the Stereoptic display, the Holographic Display will be displayed (reflected) in exactly the same way as the original object. The viewer can move and still maintain 3-D visualization from different angles. This type of technology is very complex, and like Stereoptic technology, is very expensive (Garland, Guide, Jentsch, Koning, & Wise, 1991).

The above technologies must be synthesized with current vision research, and FAA human factors requirements pertaining to the given technology. This must happen in order for the technology to be fully effective in all operational environments. In addition, the overall increase of the average pilot age signals the need for a readable and functional display that can afford the pilot all the necessary information, while decreasing workload. As we age, our focal length for clear acuity increases. The normal range being 14 to 16 inches, increasing after the age of 40. There is ample evidence showing that pilots’ visual fatigue increases with aging, especially in low levels of illumination such as in night and instrument conditions.

A-3 Workload

The amount of information being presented to a pilot during routine and emergency situations can be overwhelming. The workload encountered by a single pilot in instrument conditions many times overloads or incapacitates the pilot in command, thus, leading to loss of situation awareness. The conduct of single pilot instrument flight rules (SPIFR) operations is a demanding human operator task requiring highly efficient division of attention involving manual control, assimilation of information from a variety of sources, and the exercise of sound judgment. Although more prevalent in the general aviation flight environment, high workload considerations are still applicable to corporate and air-carrier operations as well. For the purpose of this paper, inadvertent flight into IFR conditions can be assimilated into the SPIFR workload discussion. New technologies are expected to have a dramatic impact on future controls and displays for SPIFR operations.

The potential for reducing workload will only be realized if the interface with the pilot is well developed (Hinton, D. A., Hoh, R. H., & Smith, J. C., 1987). This report presents a first step in developing the criteria for pilot interaction with advanced controls and displays. A divided attention workload model was formulated to quantify the pilot behavior required for successful operation in the SPIFR environment. This model illustrates that the human pilot's primary limitation lies in the fact that he or she is basically a single channel processor--a human operator can only tend to one thing at a time. This effect tends to be magnified in a high-workload situation. Success or failure in a given task, therefore, depends very strongly on the pilot's ability to properly divide his attention according to the demands of the situation. Two experiments were conducted, the first to determine the effect of existing controls and displays on workload, and the second to investigate fundamental requirements for future cockpits. Experiment I consisted of a flight test program conducted at NASA Langley, which evaluated pilot workload in the presence of current and near-term displays and autopilot functions. Experiment II was conducted on a FlightSafety International King Air simulator, and investigated the effects of co-pilot functions in the presence of very high SPIFR workload. Both qualitative and quantitative workload measures were used in the experiments. Autopilot functions were highly effective for reducing pilot workload in the SPIFR environment. Pilot blunders occurred at the same rate with and without an autopilot, although the nature of the errors was different. The four subjective workload measurement scales that follow were administered to the subject pilots upon completion of each IFR scenario. (1) The Multiple Scale Rating System (MSRS) for pilot workload was developed specifically for this experiment. This rating system consists of five separate scales with the adjectives "Excellent," "Good," "Fair," and "Poor." The purpose of the MSRS was to determine the specific components of workload that results in a given overall assessment. The MSRS scale has the following components: precision, ability to perform side tasks, ability to maintain mental orientation, ability to avoid blunders, and overall assessment. (2) A slightly modified version of the Cooper-Harper Handling Qualities scale for handling qualities was utilized to make an overall estimate of pilot workload. (3) A workload scale termed the Modified Cooper-Harper Scale (MCH) utilizes the decision tree format of the Cooper-Harper scale, and employs an identical structure. However, the semantics are entirely different. (4) A Subjective Workload Assessment Technique (SWAT) was developed by the Air Force which consists of three components of workload: time, effort, and stress. The workload corresponding to each of these components is characterized by the following three statements: time load, mental effort load, and stress load. The results of this study indicated that a moving map display aided the most in mental orientation, but had inherent deficiencies as a stand-alone replacement for an HSI (Horizontal Situation Indicator). Autopilot functions were highly effective for reducing pilot workload. The simulator tests showed that extremely high workload situations could be adequately handled when co-pilot functions are provided. The long-term safety implication of a successful Synthetic Vision System that will allow a pilot to see the external environment through a visual display, as well as assisting in system management is immense; increasing safety by reducing pilot / crew workload, and maintaining situation awareness.

A-4 Novice Vs Expert

In order for Synthetic Vision to be trusted, and accepted across the entire aviation spectrum, the systems must be user-friendly as well as reliable. This, combined with the quantitative information obtained from the following studies may be of substantial benefit in shaping our thinking about how pilots make decisions and in plotting our future course of research. The study of expertise seeks to understand and account for what distinguishes outstanding individuals in domain from less outstanding individuals in that domain, as well as from people in general. The approach focuses on outstanding behavior that can be attributed to relatively stable, learned characteristics of the relevant individuals. The classical expertise literature suggests that aggregation of experience (e.g., ten years of full time work in a domain) is the single most important factor in the acquisition of expertise. On the other hand, people with many years of experience in a domain performed only slightly better than those just coming out of training. Apparently, expertise in general aviation may have very little relationship with flight time after a certain number of hours-perhaps as low as 2000 hours (Chubb, Jensen, & Kochan, 1997). In this study it was concluded that the greatest amount of improvement occurs in training, not as a result of years of experience.

Four studies of pilot decision-making were conducted to formulate a general model of the expert pilot that might be applied to novice pilots in order to increase their decision-making skills and reduce their risk of accident involvement. A preliminary definition was obtained that stressed motivation, confidence, superior learning and performance skills, and an intuitive decision-making style. Another study evaluated these characteristics, as they were possessed by pilots of three types of relatively high-performance general aviation aircraft. Experienced pilots were presented with a plausible general aviation flight scenario using a verbal protocol methodology. Frequencies of subject responses in each category were tabulated for later analysis. Trends in the flight-test data indicate that pilots who achieved better overall flight results could be differentiated from those who were less successful in three ways: (1) They seek more quality information in a more timely manner, (2) they make more progressive decisions to solve a problem, and (3) they communicate more readily with all available resources (Chubb, et al.). Subjective analyses of the transcripts show that pilots do indeed have different methods and styles for solving fairly common flying situations, and these methods are not related to the total flight time or total number of years flown.

The next step for Chubb, et al., was to build cognitive models using the expertise approach, which involves three steps: (1) Identifying representative tasks that capture the essence of superior performance in a specific domain, (2) detailed analysis of the superior performance through several methods including verbal reports during performance of the tasks, and (3) efforts to account for the acquisition of the characteristics and cognitive structures found to mediate superior performances of experts.

Although general aviation can point to some successful attempts, deliberate teaching of judgment skills is rare. Crew resource management (CRM) programs in the airline environment, which are closely associated with aeronautical decision making (ADM) training, seem to be having a useful effect, but assessment strategies are lacking. In these and other studies on experts and novices, the following sub-goals are a common thread: (a) Determine the distinguishing qualities of expert aviators, (b) assess the processes by which they have acquired their expertise, and (c) create a training and evaluation system to bring the competent pilot closer to the expert. Through this process, a cognitive model was developed by Chubb, et al. This model will be used to develop a new intervention strategy for teaching these skills. In summary of this extensive study, the seven basic characteristics of what terms “Expert Decision Making” which are relevant to experts in all domains are as follows: superior memory, goal oriented, fast access, opportunistic planning, adaptive, self-monitoring, and perceptual superiority (Chubb, et al.). Also summarized in this study are primary characteristics distinguishing the expert from the competent--judgment being the primary characteristic. Expertise in General Aviation pilots can be defined in terms of the following ten characteristics:

1. Self-confidence in his or her skills as a pilot,
2. Motivation to learn all there is to know about the flight domain and practices their skills constantly,
3. Ability to focus on the necessary task and change that focus at the slightest hint that a change is needed,
4. Situation awareness (flight environment, location of other aircraft, terrain, navigation, communications, weather, etc.),
5. Cognizant of machine including noise, vibration, and engine indications,
6. Vigilant for the unusual, abnormal, or emergency, and mentally makes contingency plans,
7. Mental capacity for problem diagnosis, risk assessment, and problem resolution,
8. Communication skills and applies those skills to each audience and situation,
9. Knowledge of his or her own limitations and motivation to keep a safe margin above those limits,
10. Ego-strength to enforce his or her own limitations in every situation.

Most of the characteristics listed can be improved through proper training (Chubb, et al.). The novice GA pilot, and experienced airline captain are no exception. The importance of this information cannot be over-emphasized. There will be an enormous impact on the future of pilot training, the cost of training, and the safety of training. Cockpit automation such as Synthetic Vision, along with proper training, should reduce accidents, more specifically CFIT accidents.

A-5 Situation Awareness

In aviation the accident record shows that it is in the area of cognitive skills where pilots most often fail. Due to this and the increased reliance on cockpit automation, the need for monitoring on the three dimensions of the plane, path, and the people becomes even more critical to maintaining situation awareness. Evaluating the status of each in addition to monitoring is part of the process. Situation awareness can simply be defined as knowing what's going on so that you can figure out what to do. A definition of situation awareness by Endsley (as cited in Hartsock, Liggett, & Reising, 1997) is as follows: "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and their status in the near future". Sheryl Chappell points out that focusing on a broad region (keeping the big picture), focusing on a narrow region (pay attention to detail), and focusing on the right information (don't get sidetracked or distracted), are all essential to maintaining situation awareness (Chappell, NASA).

Another key to maintaining situation awareness, which has been echoed throughout the entire aviation community, is to anticipate; stay ahead of the airplane. Anticipation is especially important in high-workload situations such as in takeoffs, landings, and emergencies. Thinking about what will or could happen in the immediate future goes a long way in staying ahead of the airplane. Using low-workload situations to cognitively project forward into the future can minimize overload during overload times. Another way pilots can stay ahead of the airplane is by creating reminders. An advantage of the advances in cockpit computer technology is the ability for the electronic system to remind the pilot of critical tasks that are missed or forgotten; these systems have the ability to correct deviations and situational problems as well.

According to Onken (1997) new types of latent overtaxing-prone situations appeared with the increase of automated functions, in particular with respect to failings in situation awareness. New advances in technology were not followed closely by advances in cognitive engineering. Onken believes that it is time to reconsider the basic requirements for machine support in the aircraft cockpit.

Designing system requirements based on a top down structure to avoid overtaxing of the cockpit crew are mentioned in much of the research on situation awareness. Cockpit automation including cognitive engineering must comprise both comprehensive machine knowledge of the flight situation, and efficient communication between crew and machine. The knowledge base in advanced sensor technology such as computer vision, can include almost all situation elements the pilot or crew may be aware of. The Cockpit Assistant System (CASSY) allows all situational elements of the entire flight situation to be stored in a central object-oriented representation. The Dialogue Manager is responsible for extracting the decisive patterns and coordinating their output to the crew via speech and / or display. The Dialogue Manager also picks up information from the crew (inputs), and directs them to the respective module of the assistant (Gerlach & Onken, 1993, as cited in Onken). It has been shown that situation awareness and adequate workload levels can be systematically designed into the cockpit by cognitive engineering according to the basic requirements for flight deck automation. If the machine assistant has a complete picture of the situation, and the operator / pilot has incomplete situation awareness, the machine can be used to complete the picture.

One of the main focuses of situation awareness research is in the design and function of cockpit displays. The current CRT display technology imposes serious limitations on display positioning inside the aircraft cockpit--CRT size, power consumption and weight are the limiting factors. Hopper (as cited in Hartsock, Liggett, & Reising, 1997) stated that “Active Matrix Liquid Crystal Displays (AMLCDs) are the current choice for presenting information on the front instrument panel”. According to Hartsock et al., they are in, or planned for, every new commercial and military aircraft, both fixed and rotary wing.

A study by Jennings and Baillie (1997) looked at the feasibility of using pictorial and stereoscopic cues during helicopter instrument approach procedures (IAP). The study focused on two factors: the pilot’s awareness of aircraft position relative to the approach path and the landing pad, and the pilot’s ability to fly an instrument approach within defined tolerances. The pilots in this study preferred the conventional display because of its tracking capability, and its ability to lower crew workload. Pictorial display cues, according to the pilots, improved their situation awareness during approach. In addition, the pilots reported that stereo cues incorporated in the display design did not significantly enhance their ability to perform IAP. The pictorial display contained several strong monocular depth cues such as occlusion, linear perspective, and motion flow; therefore the stereo cues were of limited value. In Jennings and Balia, the pilots commented further on how the use of pictorial and stereoscopic displays affected their approaches. The pictorial displays, which gave the pilot a realistic looking view of the outside environment were said to have given as good an awareness of the situation as actually looking outside. One of the pilots in the study commented that pictorial format may be even more useful in curved or complex approaches. Two of the three pilots in this study found it easier to identify transition on to the glide slope when using pictorial or stereoscopic display. Situation awareness using the pictorial display was improved when some pilots flew outside of the tunnel full-scale display boundaries of localiser and glideslope. Although, pilots reported a loss of guidance as they neared the decision height on landing when using the pictorial display. Overall, most pilots ranked the stereo display better on the ability to fly the IMC approach within acceptable limits. But, it was concluded in this and other studies that stereo displays did not significantly improve performance as compared to the performance enhancement of pictorial displays. Large color displays with a natural looking environment seem to be the preference of the pilots in this study.

In order for the pilot to use his machine effectively, there must be good communication between him and the system. More research on the understanding of human behavior, combined with increasing the technology's ability to read the behavior of the pilot is the direction today's SITUATIONAL AWARENESS research is headed. The technology is there, but the emphasis on human behavior and interface is still lacking and needs to be at the forefront of any system design.

A-6 Terrain Data Base Certification Issues under FAA TSO-C151 (TAWS)

1. Minimum Geographical Considerations include: (a) Worldwide terrain and airport information (is desirable); (b) as a minimum, terrain information shall be provided for the United States, its territories and possessions, and the routes flown by scheduled air carriers; (c) airport information (location and elevation of runway ends and ARP) shall be provided for all runways of 3,500 feet and longer.
2. Development and Methodology: The manufacturer shall present the development and methodology used to validate and verify the terrain and airport information. RTCA DO-200, Preparation, Verification and Distribution of User-Selectable Database should be used as guideline.
3. Resolution: (a) Terrain and airport information shall be of the accuracy and resolution suitable for the system to perform its intended function; (b) terrain data should be gridded at 30 arc seconds with 100 foot resolution within 50 nautical miles and with 15 arc seconds with 100 foot or less resolution within 14 nautical miles of all airports 3500 feet or greater. Terrain data may be gridded in larger segments (up to 5 degrees squares) over oceanic and remote areas around the world.
4. Updates and Continued Airworthiness: The system shall be capable of accepting updated terrain and airport information. The FAA uses the term "terrain awareness and warning system" (TAWS) in the Notice of Proposed Rulemaking (NPRM) 97-RIN 2120-AG46. This term being used because they expect that a variety of systems may be developed in the near future that would meet the improved standards being proposed in this particular NPRM. The Volpe National Transportation Systems Center (VNTSC) investigated GPWS and EGPWS prevention of CFIT accidents in various categories of aircraft and operations. The FAR Part 91 study (GPWS not required) showed overwhelmingly that EGPWS could have avoided 42 of 44 accidents studied. The EGPWS in this study would have met current TAWS requirements proposed in this NPRM. The VNTSC study of Part 121 / 135 operations credits GPWS as a "significant" factor in reducing the frequency of CFIT accidents since 1975. Elaborating further, the study states that the "continuous

terrain display feature of EGPWS may be even more important than the terrain threat detection / alert / warning features in breaking the chain of decisions leading to CFIT. The continuous terrain display allows crews to maneuver to avoid terrain long before it becomes an obstruction to their flight path" (FAA, NPRM, 1997).

A-7 Industry Research and Development

The goal of the study by SRI International for an aerospace industry association was to determine the current status of applied artificial intelligence technology in the production, testing, and automated reconfiguration of avionics. SRI found reports of more than 60 systems that had been developed in this area by aerospace companies, government agencies, and research organizations. According to this study, the most important technology in the coming revolution in air navigation and air traffic management for civil aviation is global navigation satellite systems (GNSSs).

Most of the civil aviation communications, navigation, surveillance functions, and air traffic management systems in use worldwide today, had their origins in the WWII era. The International Civil Aviation Organization (ICAO) is coordinating the efforts to update these systems. SRI's study (full text unavailable at the time of this writing), describes the driving forces for the future air navigation systems (FANS), the issues relating to the implementation of FANS, and the expected outline of the FANS environmental implementation plan. It identifies the forces driving changes in the avionics industry and provides a detailed look at the future market for various avionics products such as communications, navigation, and surveillance avionics; aircrew interface systems; other supporting sensors; and flight control systems.

Curt Graeber, an employee of the Boeing Company Cockpit Design Department, who was once with NASA in their fatigue and sleep studies, stated, "the great challenge has become information management: what's available, how and when it should be available, and how it should be displayed" (Graeber as cited in Reinhart, 1995).

Institutions such as Carnegie Mellon University, the University of Toronto, and Embry-Riddle Aeronautical University are highly involved in the development of display technology. Private industry is highly involved in cockpit display technology also. Whether in consortium with other companies, or academic institutions, private industry has a huge financial stake in this type of technology. GEC-Marconi undertakes research in electronic systems, subsystems, components, devices and materials, in particular radar communications, sensors, avionics, and artificial intelligence and robotics. There are also facilities for the design and production of display devices. Following an intense international competition, GEC-Marconi has been selected by American Airlines as the supplier of 75 Civil Head Up Displays (HUD) for their new 737-800 aircraft. American also holds a further option for 425 HUDs that will cover their entire 737-800 fleet. According to a GEC-Marconi press release on the Internet, "the market for Civil HUDs is conservatively estimated at between 10,000-16,000 systems over the next 10 years. GEC-Marconi Avionics, Mission Avionics Division in Rochester, UK, is the world's largest HUD supplier with over 10,000 units in service (GEC, On-line).

Dassault Electronique is a major European supplier of leading edge electronic systems, software and information systems serving the military, aerospace and commercial markets. In civil aviation, the product line includes airborne satellite antenna systems, collision avoidance systems and airborne data storage and processing equipment. For a

European avionics industry, the capability to develop an onboard architecture for the future CNS / ATM (Communications, Navigation and Surveillance / Air Traffic Management) environment is of strategic importance, being the focal point of future onboard systems and therefore dominating cockpit avionics. Their proposed work will focus on data link realization and communication management and onboard CNS / ATM functions that are compatible with the future European air traffic environment, including flight plan negotiation and 4D planning / guidance (Dassault, On-line).

AlliedSignal Electronic & Avionics Systems (EAS) provides electronics and avionics for military aircraft, defense and space systems, large and regional air transport, and business / general aviation. EAS produces systems for communication, navigation, flight control and management, weather radar systems, collision avoidance systems, ground proximity warning systems, wind shear radar, runway management systems, and voice and data recorders. EAS also holds positions in development of microwave landing and electronic systems, flight guidance and control systems, sensors and components, automatic test systems and cockpit display systems. Some of their current technology in avionics is as follows: TCAS I, TCAS II, GPWS, Global Wulfsberg FMS, EFIS, Electronic Horizontal Situation Indicator, GNS-XI's, and GNS-X Flight Management System. Full color or monochrome CDU's, flat-panel displays, and active-matrix liquid crystal technology are available (AlliedSignal, On-line).

The Research and Technology organization of Boeing Computer Services (BCS) is actively pursuing two projects using virtual reality technology. According to David Mizell (Boeing, On-line), manager of Virtual Systems Research & Technology, Boeing uses a concept known as Augmented Reality rather than the more classic virtual reality configuration. Augmented Reality is a term that refers to the ability to see-through a computer-generated display. The generated images are superimposed on top of reality. Some of Boeings current research interests are as follows: design automation, intelligent graphics, virtual and augmented reality, and virtual collocation (Boeing, On-line).

The Honeywell TCAS 2000, has a display range to 80 nautical miles (nm), variable display ranges (5,10, 20, 40, and 80 nm), 50 aircraft tracks (24 within five nm), 1200 knots closing speed, 10,000 feet per minute vertical rate, normal and enhanced escape maneuvers, escape maneuver coordination, & Air / ground data link. The HUD 2020 manufactured by Honeywell and GEC-Marconi Avionics provides an advanced, lightweight, compact, electro-optical overhead unit, and synthetic hologram combiner assembly. The system is designed to meet Category II, and Category IIIa requirements. Gulfstream has announced it will develop and certify an Enhanced Vision System (EVS) in the near future for the HUD 2020. Honeywell and GEC-Marconi have designed the HUD 2020 to support such applications. The Honeywell / Pelorus Satellite Landing System (SLS-2000) uses Global Positioning System (DGPS) technology. The system, developed by Honeywell and Pelorus Navigation Systems, integrates both air and ground station DGPS requirements to enable fail-operational, fault tolerant Special Category I approaches, with growth capability to Category II and III (Honeywell, On-line).

A-8 Summary

Together with the companies listed, numerous other private and public organizations are involved with the research and production of cockpit automation technology. Also, in government and academia, there appears to be ample concern for the need to research synthetic / enhanced vision systems. Problem areas such as the ones listed in this paper seem to be the central focus of most research. There is a slow-moving realization that the human factor should be built into every system before, during, and after the production process. Even the federal government (FAA and NTSB) has stepped in to advocate cockpit automation. The FAA has recently vowed to hire more human factors specialists in order to bring the FAA up to speed on human factors and its impact on aviation as a whole. With the amount of research being conducted world-wide, on computer / synthetic vision technology, it's apparent that the future of aviation safety research will have its roots in Synthetic Vision. To bring the future closer to reality, the large knowledge gap between the understanding of human relationships with computers must be bridged by research in human-computer interaction.

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Appendix B Geodesy / Datum Issues for SVS Terrain Databases

This appendix is intended to provide an overview of geodesy and the role of datums. While a common, worldwide datum reference system is highly desirable, many of the terrain databases and maps available throughout the world were generated using datums local to the region. Without accounting for differences in these datums, significant relative errors can occur between terrain data sources.

In addition, systems that rely on navigation data in conjunction with terrain data must also ensure that the navigation system outputs are adjusted to the appropriate datum.

B-1 Introduction

Navigation systems, such as used for aviation, generate and derive latitude and longitude coordinates for aeronautical use. These coordinates are generated by airborne systems using gyroscopes, accelerometers, ground-based radio transmissions or satellite-based signals. The measurements from the gyroscopes and accelerometers are earth centered relative to the alignment of the aircraft. Satellite navigation is also earth centered due to the orbits of the satellites fixed at the center of mass. Navigational satellites, such as the Global Positioning System (GPS), broadcast time and current location in orbit, which the user can triangulate to determine position and velocity. However, radio navigation from the ground may alter the overall navigation solution computed by airborne devices due to differences in the reference frame or datum between the ground systems and the airborne systems. Fortunately, the precision inherent in radio transmissions from the ground is usually not precise enough to demonstrate this difference.

Ground-derived coordinates of latitude and longitude are somewhat different from navigational coordinates despite using the same units and definitions. Civil governments publish documents and charts of ground coordinates for making maps, boundaries, property lines, jurisdictions, and other geographically related needs. In the last two centuries, geodetic surveying and topographical mapping were closely conducted works for the purposes of measuring the earth and accurately describing the shape of its surface. Many national surveying organizations covered most of the land areas of the world by triangulation, which was ultimately referenced by a few laboriously measured base lines for control points. From these measurements, the horizontal geometry could be transformed into a plane coordinate system for constructing maps.

Astronomical observations produced angular results of astronomical latitude, longitude and bearings at points on the earth. Linear distances can not be obtained directly without the knowledge of the size of the earth. By using the nautical conversion of one minute of latitude to a nautical mile, distances between points within the limits of observational errors could be incorporated with surveys.

Relative height was treated separately by finding differences in elevation by leveling with a transit, measuring vertical angles or by barometric observations. The usual reference surface chosen for height was mean sea level, which is now determined by tidal gauges that average tides over 19 years to eliminate the precession effects in the Moon's orbit. However, even this definition varies locally due to differences in the local gravity, so other equipment such as gravimeters and pendulum clocks were used to plot the variation of the local gravity, which will be discussed in a later section dealing with height measurements.

All reference systems used by national surveys were limited to regions and local areas, because no method then was able to satisfactorily connect one survey datum from one continent to another datum from another continent. However, five new tools for surveying and geodesy have altered previous practices:

1) Aerial photogrammetry. This is now the usual method of gathering topographical details of the earth's surface for drawing maps. The choice of features can be made from a photograph and filed for future reference. However, weather may not allow a clear photograph of a local terrain, and control points on the ground must be made to provide the means of transforming photograph coordinates to the ground reference system.
2) Electromagnetic Distance Measurement. Instruments for measuring distances by timing the passage of electromagnetic pulses along the lines has revolutionized surveyed procedures in the field. Once the instruments are set up, the distances can be measured with an accuracy of a few parts per million. A survey framework can now be made with distances only, because precise transverses were limited to angular measurements.
3) Gravimetry. The gravimeter can take gravity measurements at the rate of tens of stations per day, both on land and on sea. These devices make it possible to get more precise measurements of height around the world.
4) Artificial Satellites. With satellite systems, such as the Global Positioning System (GPS), it is possible to obtain spatial triangulation to determine position and velocity over all land areas. This allows new measurements for the size, shape and gravitational measurements of the overall earth. GPS has been instrumental in connecting all surface areas of the earth to a worldwide coordinate system as a reference.
5) Computers. Electronic computers have made it possible to accomplish numerical precision and computational results without the need for intensive manual calculations or special formulas. This has also expanded the mathematical techniques for precise surveying applications and allowed the integration of computers with any of the surveying tools.

B-2 Differences in Coordinate Systems

Ground-derived coordinates of latitude and longitude are determined with measurements and calculations on mathematical reference models. These models represent the shape of the earth in a particular geographic region and are called geodetic datums.

For example, the coordinates used in the United States are mathematically referenced or calculated to the North American Datum (NAD), in Japan to the Tokyo Datum and in Europe to the European Datum. Each of these datums, among the hundreds of such systems, uses a different mathematical model that best represents the earth's shape in that specific region. The mathematical parameters of these datums differ, the location of the center of each datum differs and none of the datum centers coincide with the center of the earth.

GPS is a geocentric or earth-centered reference system. The GPS satellites broadcast their locations in the World Geodetic System 1984 (WGS-84), which uses a referenced ellipsoidal surface that approximates the overall shape of the earth with its equatorial bulge. GPS coordinates will not compare directly with local geodetic datums coordinates except in North America where coordinates are being readjusted to such recent datums as the North American Datum 1983 (NAD 83) to closely agree with WGS-84.

B-3 Air Safety Problems with Datums

Latitude and longitude coordinates provided by civil aviation agencies are referenced to different geodetic datums. These database coordinates will not accurately compare with coordinates generated by on-board navigation systems. For example, the latitude of an airport coordinate in Japan referenced to the local Tokyo Datum will differ by approximately 11.3 seconds in latitude or 1,100 feet from that same point referenced in WGS-84 coordinates. Such differences in coordinates may not have an appreciable effect on enroute navigation, but navigational safety within the terminal area is definitely impacted.

The government aviation agencies in cooperation with ICAO and other international organizations should adopt a common earth-centered geodetic reference datum for latitude and longitude coordinates. A common datum such as the WGS-84 reference datum would permit a single reference for latitude and longitude that would be compatible with all types of databases and navigation systems. GPS has had a very big impact into the field of geodesy, because mapping has been expanded into a global model of the earth that encompasses geodesy.

B-4 Geodesy

Geodesy is one of the oldest fields of science. It involves applied mathematics to combine observations and measurements of positions and areas of the earth's surface, the shape and size of the earth and variations in the terrestrial gravity. In the past, the military used geodesy for determining positions on the earth's surface for mapping or for artillery control. With the advent of rocketry, the modern requirements for distance and direction were required for space exploration, satellite tracking, global navigation of intercontinental missiles and aircraft, and defensive missile operations. This has made the requirement for a more precise determination for the figure of the earth. The actual surface is not suitable for exact mathematical computations, because the formulas that would be required to account for irregularities would necessitate a prohibitive amount of computations. While a sphere is a close approximation of the true figure of the earth and works satisfactorily for many purposes, the most nearly approximate shape of the earth is an **ellipsoid** of revolution. This is a figure defined by the radius at the equator called the semimajor axis and by the flattening, which indicates how closely the poles are nearer to the center of the earth than along the equator.

One other figure called the geoid is used, because certain instruments like the gravimeter or the plumb bob make measurements relative to that surface. The **geoid** is an irregular surface where the gravitational potential is everywhere equal and which the direction of gravity is always perpendicular. This surface coincides with the surface which oceans would conform over the entire earth if free to adjust to the combined effect of the earth's masses and the centrifugal forces of the earth's rotation.

The ellipsoid is used to compute the geodetic coordinates or positions on the earth's surface along this regular surface. Because of the uneven distribution of earth's masses, the geoidal surface is irregular, and the two surfaces will not coincide. The separations are called geoid undulations. Also, the plumb line that is perpendicular to the geoid is called the vertical, and the perpendicular to the ellipsoid is called the deflection of the vertical. The differences in these attributes are shown in Figure B-1.

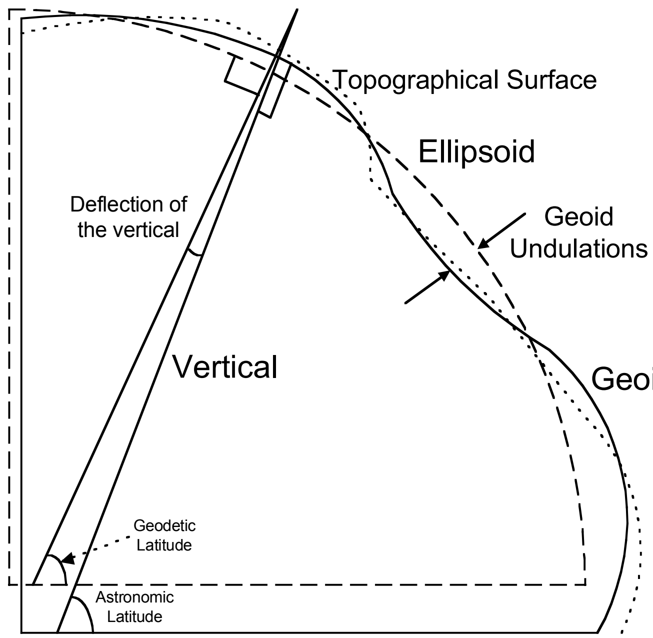
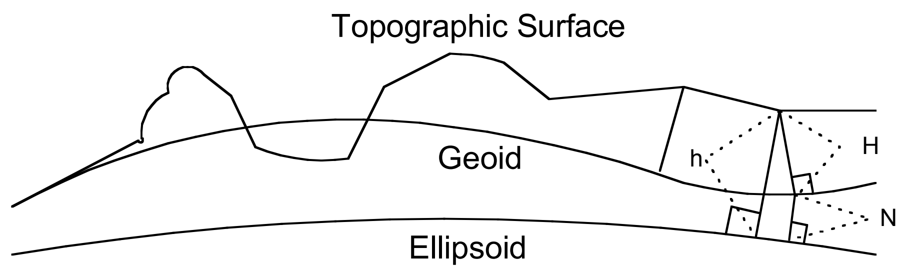


Figure B-1 Geodetic Reference Surfaces

The reference that represents elevation is called a vertical datum. Traditionally, surveyors and cartographers used mean sea level for the definition of zero elevation, because the sea surface is available worldwide. However, for inland locations, there is no tangible surface of the ocean to measure height. Although the height can be obtained laboriously using various surveying techniques, surveyors use the geoid as a close approaximation to mean sea level. Surveyors infer the location of the geoid by making gravity measurements and by modeling it mathematically.

The topographic surface is the actual visible surface of the earth. To represent horizontal positions on maps and charts, a mathematical model of the earth is needed to set the numbers for the size and shape of the earth. Because the earth is slightly flattened at the poles, a sphere won't work as well as an ellipsoid to represent the geometric model of the earth. Depending on the application, the ellipsoid, the geoid, and the center of the earth are all used as zero references. GPS receivers use ellipsoid height, sometimes called geodetic height, which is above or below the ellipsoid for WGS-84. To output mean sea level elevation as orthometric height, which is the height from the geoid, the GPS receiver must use all three zero references. Thus, if vertical datum issues are ignored, vertical errors of up to 100 meters could result.

It is also these differences between the regular ellipsoid and the irregular geoid and the even more irregular topographic surface that makes the definition of height or elevation dependent on which surface is referenced. For mapping purposes, no significant problem exists when referring to geodetic positions relative to an ellipsoid and elevations of those positions from the geoid. For precise applications, the undulations of the geoid above and below the ellipsoid must be considered. Figure B-2 illustrates the relationships between these elevations.



H - Orthometric Height (MSL)
h - Ellipsoid Height (approximately N + H)
N - Geoid Height

Figure B-2 Height Factor Relationships

B-5 Datums

A horizontal geodetic datum consists of the longitude and latitude of an initial point (e.g. origin), an azimuth of a line for direction (e.g. direction to the North Pole), the parameters of radius and flattening to define the selected ellipsoid, and the geoid separation at the origin. Any change in one of these quantities affects every point on the datum. While positions within a particular datum reference system are accurate, data derived from computations involving geodetic positions using different datums will be in error in proportion to the difference in these initial quantities. Generally, the datum is chosen to make the geoid and ellipsoid orientation such that the sum of the squares of several vertical deflections throughout the geodetic network is made as small as possible. When a datum is oriented by a single astronomical reference, the ellipsoid will not be earth-centered and its rotational axis will not be coincident with the axis of the earth. The entire network of surveyed points will be shifted with respect to the axis of the earth. This may not be significant for local usage, but it may introduce large systematic errors as the survey is expanded.

By 1940, every technically advanced nation had developed its own geodetic system to an extent governed by its economic and military requirements. Some datums were developed by expanding and unifying existing local surveys, and others were updated to replace outdated local ones. Normally, neighboring countries did not use the same geodetic datum, since no economic requirement for common geodetic information existed, and the use of common datums was contrary to the military interests of each country. The only international surveys based on one datum were for a few measurements of long arcs for the purpose of determining the size and shape of the earth. Even large geodetic systems such as the North American Datum (NAD), the European Datum (ED) and the Tokyo Datum (TD) were unable to provide intercontinental geodetic information.

As a unified world system became essential, the US Department of Defense (DOD) in the late 1950s began to develop the DOD World Geodetic System (1960), WGS 60. A combination of available surface gravity data and astrogeodetic data was used. A large-scale, least square adjustment was applied to develop the DOD WGS 72 system. Further extensive electronic and optical satellite data were incorporated for the WGS-84 model. As a result of this worldwide datum, the coordinates from one datum can be transformed to WGS-84 and then to the final datum. This permits the designation of mean sea level heights to the appropriate datum from the geodetic height of WGS-84.

B-6 Terrain Maps and Databases

Using the WGS-84 worldwide datum, the DOD has compiled a worldwide file of the global terrain by combining, reducing and adjusting various surveyed databases with new and more accurate data. The military's cartography is handled under the National Imagery and Mapping Agency (NIMA), which provides timely, accurate imagery and geospatial information to support national security. The US Imagery and Geospatial Information System (USIGS) is an extensive group of organizations that interface with the DOD and include nonmilitary cartographic organizations. The US Department of Commerce has the National Oceanic and Atmospheric Administration (NOAA) that includes the National Ocean Service (NOS), which oversees the National Geodetic Survey (NGS) and Office of Aeronautical Charting agencies. The US Department of Agriculture has the US Geological Survey (USGS). All of these government cartographic organizations have worked closely to provide a coherent worldwide database to meet the needs of military and civil users in the US.

Many terrain maps generated by these agencies are useful for SVS databases. Table B-1 summarizes these sources, which are also discussed in Section 1.3.1.3.

Description	**Database Density (Grid Spacing)**	**Horizontal Accuracy**	**Vertical Accuracy**
1° Digital Terrain Elevation Data (Level 0)	1 km	50 m	30 m
1° Digital Terrain Elevation Data (Level 1)	100	50 m	30 m
1° Digital Terrain Elevation Data (Level 2)	30 m	50 m	30 m
1° US Geological Survey (USGS)	90 m	50 m	1 contour
15´ US Geological Survey	60 m	25 m	1 contour
7.5´ US Geological Survey	30 m	15 m	2/3 contour
7.5´ Digital Elevation Map (USGS)	30 m	13 m	14 m
Digital Elevation Map 1 Degree (USGS)	90 m	130 m	30 m
1° Digital Feature Analysis Data (Level 1)	1 km	130 m	10 m
Airport Safety Model Data (6 sq. radius nmi)	180 m	50 m	30 m
Airport Safety Model Data (50 sq. radius nmi)	450 m	50 m	30 m

Table B-1 Terrain Data Sources